Determination of a Set of Cognitive, Procedural and Learning Competences Owned by Qualified Physicists

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Abstract

The aims of this research were: to define a set of physics competences and explore their mastery by a population of physics learners who had succeeded to achieve at least the A level physics qualification, or an equivalent; to find the extent of physics learners' competences that enabled success, hence creating a positive and inclusive narrative in physics learning.

Physics learning was explored using data collected by an online questionnaire from 657 respondents of gender parity, aged 18-75+years, 98% of whom were STEM graduates. 38% had graduated as physicists, 31% as engineers, 29% other STEM subjects and 2% non-STEM

Physics Competences were identified and categorised as Representation, Experimental Investigation, Problem Solving, Thinking and Reasoning, and Modelling. These were derived from the work of researchers Niss and Dolin and authorities on physics, which included the Tuning Committee and the Institute of Physics. These Physics Competences were described by 46 Indicators in everyday language to provide a common understanding for all stakeholders – students, educators, assessors and employers – of doing physics and what is required to succeed in physics. The Indicators were scored by respondents on a four point scale as a measure of mastery of physics and thus ranked the indicators on levels of challenge. A mathematical data handling process converted the four point scale to a continuous scale of bell shape distribution, as a calibrated Scale of Mastery for the STEM graduate respondents.

Participants also undertook a self-assessment as physics learners, choosing from a list of 69 descriptors that encompassed Learning Characteristics, Learning Competences, Physics Identity and Cognitive Competences, to produce a Physics Learning Profile.

Significant gender differences were found for both the mastery of Physics Competences and the Learning Profile. Within these differences, the Physics Identity of males was self-reported with a stronger cognitive competence narrative while females expressed a stronger procedural competence narrative. In both cases, especially among physicists, the academic qualification by gender were equally distributed at all levels of education from A level to PhD.

Narrative responses on challenges to learning physics found the most negative impact related to the school environment, its policies and culture. 37% of female physics learners had to counter stereotypes, lacked peer support and lacked validation of their physics ability. 55% of all respondents reported on heuristic learning in their childhood and teenage pursuits that had induced physics interest, developed investigation skills and established prior knowledge which helped elucidate and consolidate physics understanding.

86% of the non-physics-graduate respondents reported the benefit of a physics grounding in supporting and furthering their careers, through transferable cognitive competences and acquired subject related competences.

The findings and outcomes of this research are a Learning Profile and a Scale of Mastery of a set of Physics Competences. These provide a signature by which potential students of physics could self-identify and assess their physics learning capacity. These outcomes may encourage greater uptake of physics at A level and inform on mastery of physics for success.

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Introduction

Today's sustained exponential growth in technological advancement in both national and global infrastructures (Powell and Snellman 2004) and the extensive reliance on scientific knowledge within the Knowledge Economy, means that the demand for physicists and other Science, Technology, Engineering and Mathematics (STEM) educated people is high, (UKCES 2016). The emerging Artificial Intelligence, AI Economy will push this demand higher. It may be a consequence of this high demand that the UKCES sets physics graduates among the top ten highest paid university graduates. (Montgomery 2020).

It is widely recognised that those who have studied physics have specific capabilities and capacity to achieve, as well as expert knowledge that fits a broad employment spectrum (Bailey 2017). Based on data about physics graduates, many have access to non-STEM careers and go into business and finance (White 2018; Overton and Hanson 2010). This diversity of career options is promoted by most universities to encourage uptake to physics degree programmes. By contrast, post degree literature laments the loss of physicists and engineers from employment in physics related careers to other areas of employment, contributing to the STEM Skills Gap and the 'leaky pipe' analogy (Clark Blickenstaff 2005).

The Wakeham Review (2016) stressed the urgent need to produce more STEM graduates with the emphasis on their progression into STEM careers. Of these STEM shortages, supply is acute in the case of physics, computing and engineering. As a general rule, those following careers in computing and engineering will have studied physics to at least A level. Hence there is a strong argument for encouraging more school pupils to study physics up to A level, or its equivalent and then recruit on to STEM degree courses.

This research holds with the positive; that the attributes and abilities of physics learners are valuable to a diverse range of careers. The progression to non-STEM careers should be considered valuable as the leaky pipe analogy is only a problem because the numbers studying physics are too low.

Therefore, this research asks, what are the levels of intellectual behaviours, aptitudes, cognitive processing, creativity and conceptual thinking that makes for a successful physics learner and is there a specific learning environment that enables and nurtures progress and success in physics.

At the outset, it was decided that these factors would be considered in their broadest sense, and in relation specifically to physics, termed competences, as competence includes the knowing and understanding applied with each.

Aim + Objectives

As knowledge bases continue to grow and information technology expands the learning pathways, traditional education delivery needs to adapt; a competency based education infrastructure offers a solution. Defining a competency based physics education aligns well with the outcomes of two decades of physics education research in this regard. (Jones and Voorhees 2002)

The aims of this research were:

- To identify, collate and define a specific set of Physics Competences, identifying the Cognitive Competences and Procedural Competences within.
- To design a Scale of Mastery for this set of competences and define its calibration to the respondent population.
- To produce a reflective study of a group of adults who were physics learners throughout secondary school to A level or its equivalent.
- To identify respondent's student Learning Characteristics, Learning Competences and levels of Mastery of Physics Competences.
- To define a Physics Learning Profile as a measure of a successful outcome in physics learning and
- To investigate the impact of formal and informal learning environments on the physics learner.

The Objectives of this research were:

- To collect data from a representative population of physics learners for a rigorous statistical analysis.
- To give equal voice to male and female physics learners so that findings are gender neutral or show reliable gender specific trends or needs, if such exist.
- To use definitions, an experimental framework and psychometric measures as described by leading physics authorities, educationalists, psychologists and social scientists for a validated and robust study.

There were two Target Outcomes.

a. A holistic view of the competences of physics learning and their inter-relationship.

b. To identify the learning components that relate to success in physics.

Research Questions

Three core research questions were identified that would help to address the aims of the project:

1. How can a set of Physics Competences be developed and can a Scale of Mastery be defined to determine a threshold to success in Physics?

2. How do those who have studied physics 'post 16' self-identify their Cognitive and Procedural Competences, Learning Competencies and Learning Characteristics and are there demographic differences?

3. Are there other factors which lead to success in Physics?

Thesis Overview

The aim with this study was to provide a new, positive narrative and signposting on how to succeed in physics.

The Introduction, Aims and Objectives, set out above explain the research in the context of future physics education needs. Physics education curriculum and pedagogy must meet the demands of the current Knowledge Economy and the emerging technology led economy arena with their new trajectories and careers. The three Research Questions outline the scope of the data collection and analysis.

The study identified, collated and explored competences for doing and learning physics of an adult population who had at least one nationally recognised qualification in physics post-16; A Level physics or its equivalent. Data was collected by an online questionnaire.

Chapter 1 Literature Review A literature review focused on the Physics Education Landscape that lays out the problem of shortage of physics-qualified students, with reference to the extent of the problem by the stage of senior level in secondary schools**.** It also summarises Learning as described by leading educationalists and identified Models for Learning that are relevant to physics.

Chapter 2 Theoretical Framework Education Competences are identified as the best criteria by which to explore the successful study of physics. Cognitive and Procedural Competences are defined and Physics Competences compiled from literature, based on the definitions of physics and 'doing physics' as described by leading physics authorities and physics educationalists; in this way defining the foundations of data collection of this research study.

The Theoretical Framework is determined, based on the evolution of Physics Education Research to date. The Experimental Design for data collection is outlined with features for optimum data collection and how this study compares and contrasts with other Physics Education Research in the last two to three decades. Both frameworks describe the under-pinning of the data collection process.

Chapter 3 Methodology and Method Defines the Learning Constructs (that is the abstract ideas and underlying themes) and Competences to be identified and measured in the study and how they relate to physics learning. The method of operationalisation used for each construct and competence, to synthesise lists of Indicators as empirical units of measure are described.

A set of five Physics Competences are defined and processed to produce 46 Indicators as units of measure. The method of creating a scale, to measure mastery of the physics competences is explained.

The process of validation of all Indicator statements and validation of the form of the questions and the questionnaire is set out. A pilot study covers the validation of the questionnaire as an effective and efficacious means of gathering data, in a format that would facilitate appropriate quantative and qualitative data analysis.

This chapter also includes the discussion of: a mixed methods data collection, the structure and contents of the questionnaire, guidance for participants, collection of context information as demographics, the means of access to the appropriate target population, launch and circulation of the online questionnaire.

Chapters 4-8 are Results and Discussion

Chapter 4 Results - Demographics of Respondents. This is an analysis of the participants' demographics and therefore defining lenses of analysis.

Chapter 5 Results - Physics Competences and Physics Mastery. This chapter is specific to physics competences, the doing of physics and the spectrum of mastery and how this appears on the defined four point scale. It discusses the indicator components and how these are ranked according to level of challenge. A correlation analysis matrix is set out as a heat map to aid identification of specific features of individual Indicators and the inter-relationships of Indicators and Competences. The mastery scale is evaluated with reference to the A level achievement of respondents with features of the five competences discussed in relation to two ranges of A level grade attainment.

The scale for Mastery is evolved from the four point scale to a continuous distribution, created by a mathematical method. Since 98% of respondents were STEM graduates, and over 70% were high achievers according to A level grade scores, the scale is calibrated in this regard.

Chapter 6 Results - Learning Profile. Gives the results for the respondents' overall Learning Characteristics and self-reported Learning Competences to produce a Learning Profile for physics. It explores this learning profile of the physics learner according to gender, GCSE/O Level qualification and subsequent STEM degree qualification to determine what/ if anything distinguishes a physicist.

Chapter 7 Results - Other Factors of Success in Physics. Through the respondents' own narrative, certain strengths which students employed/acquired in their learning and doing physics were identified. It highlights how many respondents dealt with the challenges to their learning to achieve success.

Chapter 8 Results – Phenomenographic Analysis. With the benefit of hindsight, respondents gave a holistic assessment of their physics education. The impact of gender, socioeconomic background and their self-assessment of their academic ability, achievement and performance. Beyond the classroom, respondents' identified what had contributed to the development of their interest in physics and enabled, enhanced or consolidated their learning.

In addition to exploring what brought about success in physics learning for the student, the narrative responses were also used to examine how having studied physics supported career success; exploring how respondents reported on their 'physics grounding'.

Chapter 9 Conclusion The study produced outcomes and findings in the form of a set of five Physics Competences and 46 Indicators and a Mastery Scale. In addition a Learning Profile as a measure of what it takes to succeed in physics learning was created and the distillation of specific challenges and enablers to success have been identified and categorised.

From both findings and outcomes, conclusions are drawn on how this assessment of past physics success can direct improved opportunity for future physics students.

Appendix A – Personal Perspective on the Research Study

Appendix B – The Questionnaire

Appendix C – Question 12: Numeric Codes for Data Analysis

Glossary

References

Ethical Review: This research has been approved by the University of Leeds, School of Maths, Physical Sciences and Engineering Research Ethics Committee on 4th May 2018 ref MEEC 170024

Chapter 1 : Literature Review

This literature review focused on the context of physics education at post 16 years, finding the foundational information to produce the theoretical framework of the study and support in the development of the methodology. The body of relevant research is published in journals for Psychology, Science Education and Physics Education Research. Other sources include UK and International Government education reports, in which the analysis comes from primary sources of research by direct observation, interviews and surveys with students and educators of physics. Analysis of national and international surveys and statistics of examination assessments and the peripheral information of the examined candidates provides further evidence.

Thus the Literature Review encompassed the following five areas:

Access to Physics : The Physics Education Landscape: A comparison between recent and historical statistics for the uptake of physics in schools at secondary level: the external factors that play into these figures and correlate with their trends.

The Physics Learner: Theories of Learning, Cognition and High Level Achievement and Integration with the Learning Environment

Competences: The term competences is used in this research, The review defines the term and examines its use in relation to physics education.

Theoretical Framework: Locating the project within Physics Education Research (PER) and defining the novel perspective of this thesis**.**

Experimental Design: The theories that can be brought together to underpin the process and format of data collection and analysis of outputs and determination of outcomes.

1.1 Access to Physics: The Physics Education Landscape.

Focusing this literature review on the most recent two decades, the physics education landscape is summed in terms of:

- Uptake of Physics – The Statistics
- Perceptions on Difficulty in Studying Physics
- Girls in Physics
- Ethnicity and Socio-economic Hurdles, and
- The Student Perspective

1.1.1 Uptake of Physics – The Statistics

The low numbers of students studying physics post 16 and at graduate level has an impact on the UK economy as the supply line of physicists, engineers and physics teachers fails to meet the demand. With the growth of modern technology and therefore a growing demand for more physicists, engineers and physics teachers, the situation becomes more acute and therefore the Government and related bodies monitor the situation. The various departments within, or associated with, the UK Government, such as Department of Education, Business, Energy and Industrial Strategy (formerly Business Innovation Energy and Skills BIES), use data analysed by the National Audit Office and by organisations which advise the government on education policy: Institute of Physics (IOP), Engineering UK, Campaign for Science and Engineering (CaSE), Confederation of British Industry (CBI) and the National Centre for Universities and Business (NCUB).

The statistics conveying the position of physics in relation to the other STEM subjects are summarised in Figure 1-1 which represents the trends for uptake of physics at Advanced Level in UK schools, with data for England and Wales as representative of the whole of the UK i.e. A Level (equivalent to A Level in N. Ireland and Scottish Highers). The graph was created by the IOP and shared by Charles Tracey, IOP (personal communication). It was compiled with data from the Department of Education for England and Wales. UK. Government (2018)

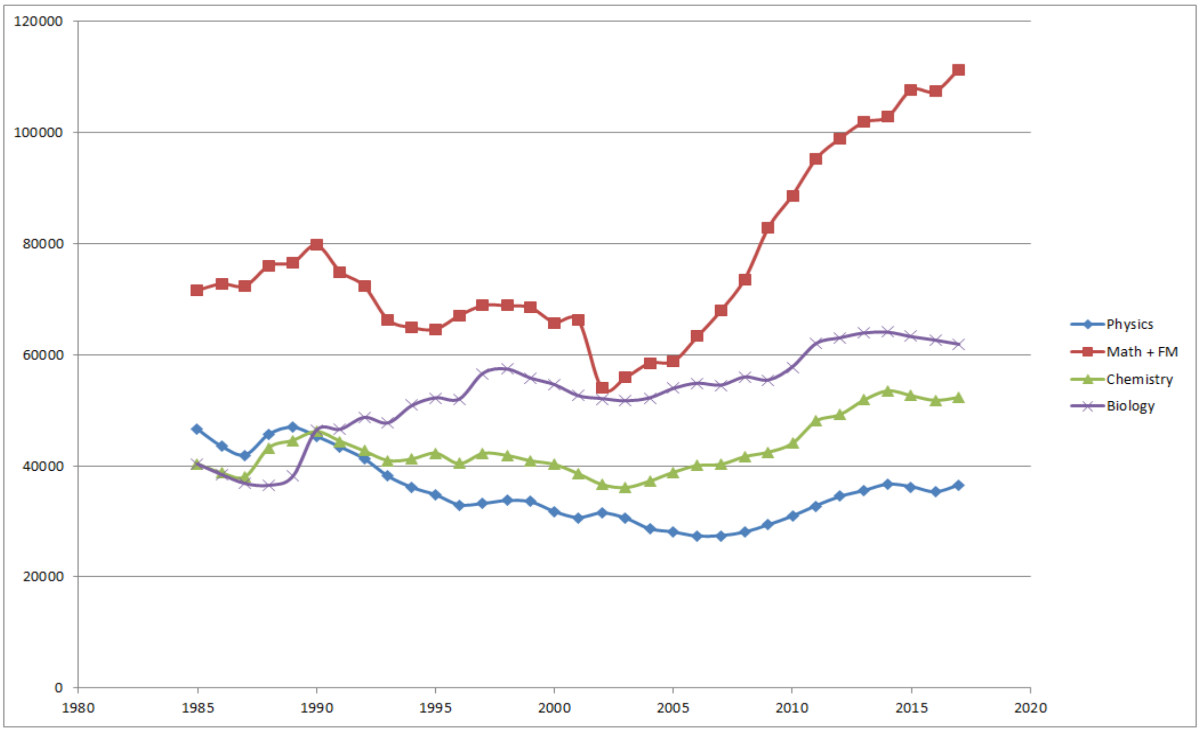

Figure 1-1: Uptake Student Numbers of STEM subjects at A Level from 1985-2016 Source: Tracy, IOP 2017

The data represents the summed impact of all influencing factors that must contribute to the problem of such low uptake in the subject and the resistance to change. Physics numbers dropped in the mid-1980s, which the IOP attributes to the change to the Combined Science qualification. Whatever the trigger, numbers continued to decline. A sustained effort with various STEM initiatives to reverse the trend and increase the number of STEM students did improve uptake in Chemistry and Biology and in particular Mathematics and Further Mathematics, however Physics appears more resistance. Figures for Physics have reportedly shown a 2% increase since 2017.

Historic Figures:

- 1960 15% of all A level entries were physics
- By 1980 - down to 9% - 58,000 students
- By 2010 - down to 3.6% (Warner 2016)
- By 2017 - up to 4.2%
- Most recent figures 2019 are in the order of 40,000 – an increase to 6.2%

Physics progression from State Schools:

- 2968 schools send 1+ students to A level physics
- 673 send no students on to A-level physics
- Over 75% of AS-level physics students came from just 27% of state schools (Tracy 2017)

Girls in Physics (England and Wales)

- 21% of A-level students are girls (1985-2016) cf. ~ 28% in N. Ireland. ~30% Scotland but the timeline trends are similar.
- 2832 schools send 1+ girls to A Level physics
- 1346 schools, 49% of Co-Ed send no girls to A-level physics (Tracy 2017)

In 2019 the percentage of female students in Physics had risen to 22% and then in 2020 to 23%.

These statistics from IOP are compiled from the Department of Education statistics. The most up to date statistics are given in the National Audit Office (N.A.O) report (2018) and show that, as a response to remedial action, the number of students studying Biology is now at a sufficient level to match employment demands. However the situation for Physics and Computing Science shows again that measures to improve uptake are not having sufficient effect and further changes must be made to address the problem.

1.1.2 Perceptions on Difficulty in Studying Physics - Examination Options and Grade Boundaries

Cole, Searle, Barmby, Jones and Higgins (2008) examined the relative difficulty of school subjects based on examination results (UK. Government 2018), Figure 1-2. The study was commissioned by SCoRE (Science Community Representing Education). By comparing five different methods of statistical analysis they found that a reliable comparison could be made between data on different subjects with consistent differences over time. They found that by comparing GCSE results and A. Level results they showed consistent differences in the grades achieved for the STEM subjects to indicate that they are more difficult, or more difficult to achieve high grades in, than other subjects and physics the most difficult to achieve higher grades of the three sciences.

In the 1980s the UK exam boards introduced a new Combined Science GCSE qualification, Biological Science and Physical Science, and changes to exam assessment. With the option to study the three single sciences only available for some students this led to a two tier system by student selection. Students identified as higher achievers were, and still are, directed to the single sciences (Gill and Bell 2013) which reinforces the perception that the physical sciences are subjects only suited for the high achievers. Cheng and his co-authors, (1995) discovered that students who take separate sciences at GCSE are more likely to continue studying science post-16, compared with students who have taken the dual-award, Combined Sciences qualification.

By comparing the GCSE results of students gaining grade A and B in physics and other subjects, to grades achieved at their A. Level, Charles Tracy, Head of Education, IOP found that in non-STEM subjects the GCSE results were a reliable predictor of like results at A Level whereas this was not the case for physics (2016). Tracy concluded that Physics exams seem to be more demanding in their expectations of student performance to achieve each grade level, or student's papers are marked 'down' more often at A. Level than other subjects. Perhaps consequently, in recent years schools deter students from studying physics unless they are very strong candidates such that, although fewer study physics A. Level, a higher proportion of A grades are achieved compared to other subjects, hence re enforcing the stereotype.

One interesting feature of
Figure ***1-2*** is that the maths and further maths have exceptionally high percentage of students achieving A*and A grades compared to all other subjects. Considering the high use of mathematics in physics it would be expected that this strength in mathematics would improve physics score outcomes but this has not occurred.

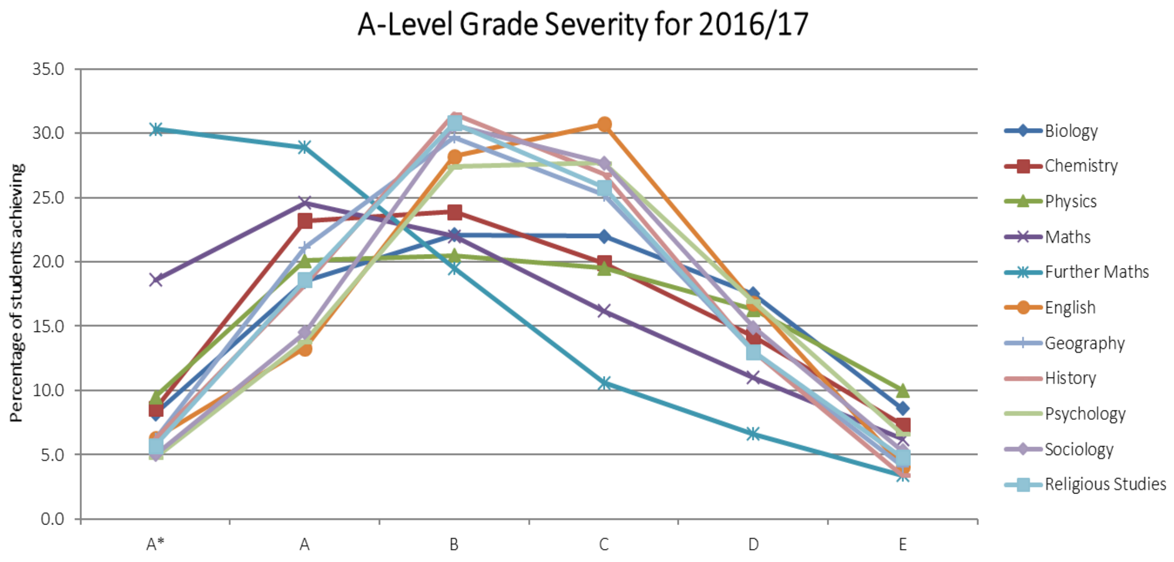

Figure 1-2: Comparison A level Grade by School Subjects. Source: Cole et al. 2008

1.1.3 Gender Differences in Studying Physics

Figure 1-1 and the corresponding statistics given in section 1.1.1 show that in the period 1985 – 2016, girls made up on average just 21% of A level Physics entries throughout the UK, except for in Scotland were the percentage is better at roughly 30%. Figures were reported to increase for 2019 and 2020 to 22% and 23% respectively but these figure disguise the fact that the absolute number of students had decreased (mainly boys) by over 1000 to 8731.

Since 2005 throughout the US, UK and European countries the number of female students at university across all subjects exceeds the number of male students, (OECD 2014). In the UK, females now make up 59% of all undergraduates and in courses for Medicine and Veterinary Medicine ~60% of students are female. For these courses the majority will have taken physics A level. Schoon and Eccles (2014) conclude that although well qualified in maths and physics, females steer towards careers in health and life sciences to satisfy their identity construction and self-affirmation in high status careers

Looking at the data that confirms the abilities of female students, Luigi Guiso's research team (2008) studied the PISA data of 2003 (Programme for International Student Assessment) for mathematics and reading. Inspecting the data against a gender equality measure, World Economic Forum's Gender Gap Index, they found that social conditioning and gender biased environments can have a large effect in test performance. Yet the OECD Report (2014) showed no significant difference in the interest and engagement of boys and girls in science

In the UK further evidence on test scores for girls can be seen in the data from the Government's Department for Education and Schools (DFES) which shows girls have outperformed boys since 1978 (McNally 2005).

Social scientists suggest the influence of changing attitudes towards raised ambitions and expectations for girls from teachers and parents has resulted in better test scores. This would also explain the significant increase in the number female students at university. (Francis 2002; Schoon and Eccles 2014)

The Institute of Physics monitors all the above and has in recent years conducted their own research based on the data from the National Pupil Database. As a result they have produced two publications, *It's Different for Girls* (IOP 2012a) which looked at the challenges for girls studying physics. Based on these finding a second report was produced *Closing Doors (IOP 2013)*. This research showed that the gender biases were the result of whole school cultures and therefore a new project *Opening Doors* (IOP 2017b) has been funded by the UK Government to pilot strategies that could address these whole school biases.

This project worked with 10 different schools to trial a gender equality Kite Mark, during the 2016/17 academic year based on the positive outcomes of the earlier Stimulating Physics Network project, in which participating schools increased the number of girls taking A level physics threefold. Participating schools carried out a self-assessment against a set of principles, which are based on research by King's College London and the IOP

The above research suggests that the issue appears to be girl's physics identity and the importance of the perception of others. These are two features that are examined in this research.

1.1.4 Ethnicity and Socio-economic Hurdles

Students from some ethnic groups and those of low socio-economic background were found to have low science and science careers aspirations. This was the finding of a longitudinal study by Kings College; London, the University of Leeds, University of Cambridge and the Institute of Education; University of London as part of the Targeted Initiative in Science and Mathematics Education (TISME) projects by Archer and Tomei (2013). Two of the projects, ASPIRES and Understanding Participation rates in post -16 Mathematics And Physics, (UPMAP) looked at children's aspirations at age 10 -14yrs and rates of uptake of physics and mathematics post 16yrs. The ASPIRES project surmised the factor which deterred student choice in STEM to be low Science Capital, although with the difficulty of measuring Science Capital in any correlation study to date, the project did does not have the capacity to confirm this.

The impact of socioeconomic status on entry to physics is one factor that is quantifiable. Low Socioeconomic status (LSE) is often measured as those pupils who are eligible for Free School Meals (FSM) Figure 1-3.

The Figure clearly shows a widening gap in the number of LSE pupils entered for GCSE physics compared to their HSE peers, with a significant disparity in the last decade.(SEEdash 2017)

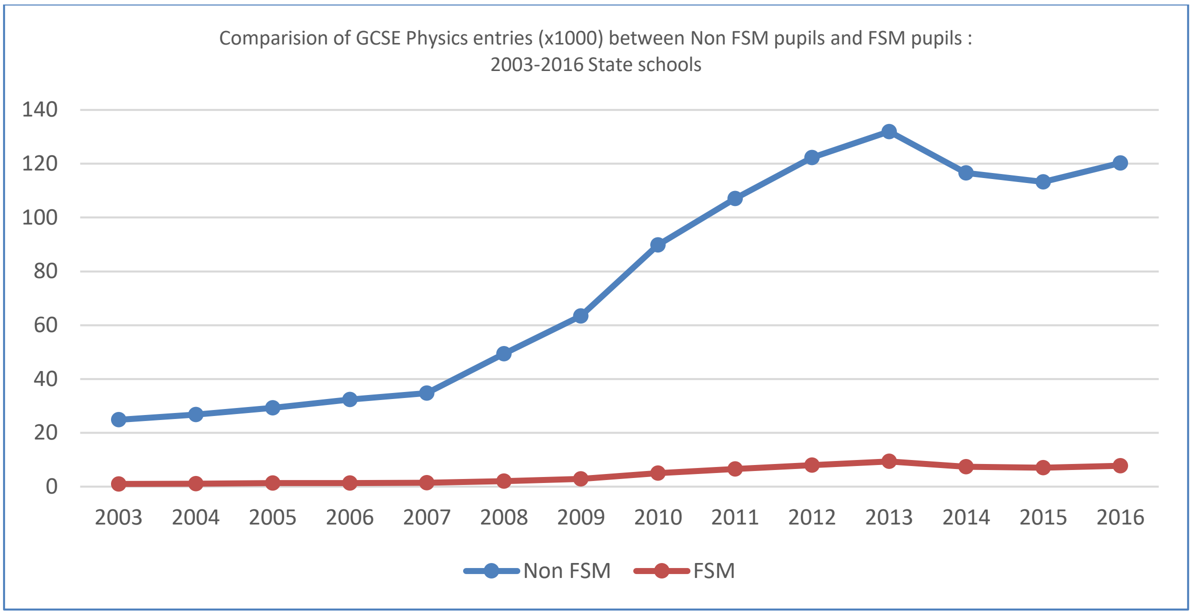

*Figure 1-3: Comparison of GCSE Physics entries: HSE and LSE students***.** *Source: Sci. and Eng. In Educ. Dashboard (SEEdash 2017)*

Furthermore, it is evident from Murphy and Whiteleggs' Institute of Physics paper (2006) that physics suffers from the most significant socio-economic inequalities of any school subject for participation by students. In consequence the IOP launched a campaign to address this matter. (IOP 2020)

Although this PhD research study did not probe socio–economic background directly, questions on which schools respondents had attended provided an indication and respondents offered this type of detail in response to free narrative questions Q18-21.

1.1.5 The Student's Perspective

Considering all the above factors which are likely to each play a part in the complex cause to low uptake in physics, it is both important and interesting to take the perspective of the student. Research by Tamjid Mujtaba and Riess at the Institute of Education, University College London (2012) as part the UPMAP project found that young people are more likely to continue mathematics and physics post-16:

- If they have been encouraged to do so by a key adult – either a family member who believes in the worth of these subjects, or a teacher.
- If they believe they will gain from studying the subject in terms of job satisfaction or material rewards such as a good salary.
- If they are good at the subject and can show they understand it in depth.
- If they have been well-taught.

These UPMAP reported influencing features reported by thirteen to sixteen year olds are compared with the influences reported by the respondents of this research study as the adult respondents reflecting with hindsight on what influenced their choice to study physics.

1.2 The Physics Learner

For this research study the retrospective views were gathered of how the adult respondents managed to succeed in physics at secondary level as Physics Learners. In determining a theoretical framework for the study it was important to look at: a) what brings about success in physics and b) what are the influences and conditions for future learners.

These two aspects determined the type of data to be collected and how questions would be framed, so that the learning and understanding of physics could be captured as questions which were not physics subject problems to be solved but instead related specifically to the various physics disciplines and drew on an experience of solving physics problems.

Focusing on the Learner, this section summarises the most up to date theories of learning based on the lifetime studies of the eminent Education Theorist and Cognitive Scientist Knud Illeris (2003) and Education Researcher and Practitioner, Professor Deborah Eyre (2009; 2016b). The combination of the Illeris Theory of Learning and Eyre's definition of High Performance Learning, form the theoretical framework for this research.

1.2.1 Theory of Learning

Illeris (2003) explains the complex frameworks in which learning takes place - acquisition of content, personal development and the cultural and social nature of the learning process.

"…*all learning includes two essentially different types of process, namely an external interaction process between the learner and his or her social, cultural and material environment, and an internal psychological process of acquisition and elaboration in which new impulses are connected with the results of prior learning. Secondly, that all learning includes three dimensions, namely, the cognitive dimension of knowledge and skills, the emotional dimension of feelings and motivation, and the social dimension of communication and co-operation* " (Illeris 2003)

Learning = **External Interactions** + **Internal Psychological Process**

The interaction of the Learner and their Social, Cultural & Material Environment

Acquisition and Elaboration

Figure 1-4: Definition of Learning by Illeris

It is in negative External Interactions that barriers to science learning exist whilst positive External Interactions support learning. The Internal Psychological Process of acquisition and elaboration relate to the cognitive demands of learning

This Internal Psychological Process is made up of Content and Incentive which are two parts of the Dimensions of Learning. The third dimension is Interaction with the learning environment, as shown below in Figure 1-5, based on a schematic by Illeris (2003)

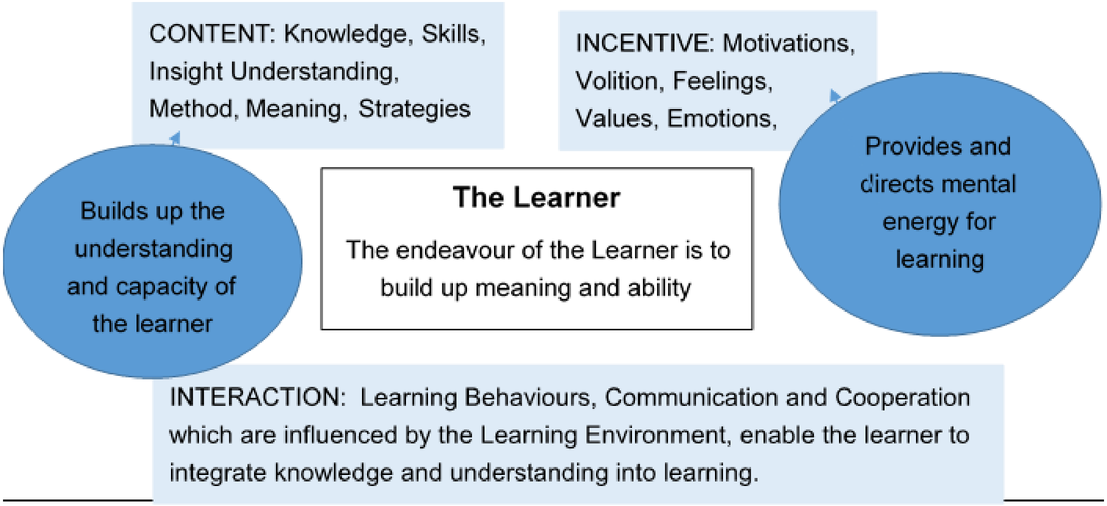

*Figure 1-5: The Three Dimensions of Learning and Competence Development - Based on a schematic by Illeris***.**

The Content and Incentive Dimensions are crucially dependent on the interaction process between the learner and the environment – social, cultural and material. The Interaction Dimension provides the initiation to learn. This initiation may take the form of perception, transmission, experience, imitation, activity, participation of knowledge. Illeris (2003)

There are also issues which influence learning without being directly involved in learning. Illeris uses the term ‘Conditions of Learning’. Internal Conditions of Learning are features of or in the learner that influence learning possibilities and are involved in the learning process. External Conditions of Learning are features outside the learner that influence learning possibilities involved in the learning process. These are in the immediate Learning Space and Learning Situation. The Learning Space would be school, work, internet based learning, interest based learning etc. and the more general cultural and societal conditions.

The Learning Situation is the interaction, in this case, in a school setting and could include the impression of the teacher, other students, the subject itself or the school situation.

Illeris concludes that learning is a very complicated matter for which all three learning dimensions must be considered. Therefore this research incorporated all three dimensions; Content, Incentives and Interactions in the data collection. Data was also collected on the Learning Conditions of Learning Space and Learning Situation.

1.2.2 High Performance Learning and Physics Learning

It could be assumed that physics is best suited for high achievers, with the low numbers studying physics. Samuel Strauss' book *The Gifted and Non-Gifted* was based on his work from 1946 to 1966 of young science doctorates and their professors (Strauss. 1981). Strauss researched the career choices, intelligence, IQ tests, school marks, family and personal backgrounds of these scientists. He then researched their creativity and research ability to show that these are within the reach of the non-gifted as well as the gifted. Hence Strauss presented his hypothesis as to the forces which drive people to reach these intellectual heights. This thesis was that average, as well as gifted children, have "untold potentialities" for intellectual achievement.

- In conclusion Strauss found that "*One can never tell which youngster will make his mark. Every human being has untold potentialities, which cannot be measured or even identified, but which may grow and flower under the right conditions".* And indeed, the eminent scientists Newton, Linneas, Darwin, Pasteur and Einstein had not been considered gifted boys.

Key findings were:

- Most gifted adults studied were not gifted as children.
- Somewhat above average intelligence is sufficient to become a scientist
- The single most important trait of achieving success is perseverance.

Reading this early research by Strauss in part inspired this research and it led to the choice of the work of Deborah Eyre to be part of the theoretical framework.

Eyre's work shifts the focus from the theory of learning to the practice of learning and applied in this research to 'doing physics'. Physics is regarded as a demanding subject to learn (Cole *et al.* 2008). To help future physics learners and encourage more to choose to continue their study of physics, understanding and exploring the learners that succeed yields an important perspective.

Eyre's early work focused on observing the learning practices apparent among gifted learners. Her theory for High Performance Learning and its practice built on her education policy paper. *(Eyre 2010)* in which she asserts that high academic performance can be a reality for many students, not just the few.

The culmination of Eyre's work is a framework for the systematic teaching of students to be 'intelligent' in what Eyre describes as Advanced Cognitive Performance (ACP) Competences as Meta-Thinking, Realising, Linking, Analysing and Creating (Eyre 2016a). Recognising ACP as an essential feature in physics learning, the author assigns this framework as Learning Competences in this work. These Learning Competences can be subdivided into two sets: Meta-Thinking and Realising as part of the Interaction Dimension (dealt with here), and Linking, Analysing and Creating as part of the Content Dimension in Chapter 2. Eyre also describes Learning Characteristics of Values, Attitudes and Attributes. These are expanded on in Chapter 3 and incorporate the work of Potvin, Hazari, Ryan, Deci, Edward (Potvin and Hazari 2013; Ryan, Deci and Edward 2000; Hanze and Berger 2007).

Learning Characteristics and Learning Competences are relevant to all learners and therefore development and strength in Learning Characteristics and Learning Competences could be a key factor for success. In addition, the physics learner can be ascribed with a Physics Identity as defined by several educationalists (Hanze and Berger 2007; Berger and Hanze 2009; Hazari *et al.* 2010; Scott. Tyler *et al.* 2014). Motivation, both internal and external, makes up part of the Physics Identity.

Hence the Learning Dimensions described by Illeris can be blended with the practice work of Eyre to define the Learning Characteristics and Competences that can be mapped to physics to describe a Physics Learner. In addition it is recognised by Hazari and others that the physics learner must have a Physics Identity. These connections are set out in Table 1-1

Table 1-1: Learning Dimensions

Learning Dimensions	Constructs and Competences	Defined in
Content	Physics Competences	Chapter 2
Incentive	Physics Identity Learning Character	Table 1_2 Table 1_3, 1_4
Interaction	ACP Learning Competences (Meta-Thinking , Realising) ACP Learning Competences (Linking, Analysing, Creativity)	Table 1_ 5, 1_6 Chapter 3

The following tables define the variables from peer reviewed sources which are used in the operationalisation process to create a questionnaire for data collection.

Table 1-2 Definitions of Physics Identity compiled in Hazari (2013)

Table 1-3 Learning Characteristics; Variables of Academic Self-Concept, Academic Goal Orientation and Uncertainty Orientation are defined by Hazari et al.(2010).

Table 1-4. Values, Attitudes and Aptitudes Learning Characteristics are taken from the work of Eyre and further expanded as secondary variables, Eyre (2016a)

Table 1-5, Table 1-6 Learning Competences, Meta-Thinking and Realising, Eyre (2016a)

Table 1-2: Physics Identity Construct and Definitions of Variables

Physics Identity Variables	Definition of Physics Identity Variables
Perception of Ability to Understand /Perform Physics	Self-assessment of academic ability and ability 'to do' physics
Desire to Learn	Self -Explanatory
Self-Efficacy :	One's belief in innate ability to achieve goals- will put in effort and overcome challenges
Perception of Recognition by Others	A view on how others rate your performance/status as a physicist or scientist

Table 1-3: Learning Character Construct and Variables

Learning Character Variables	Definitions of Learning Character Variables (some further defined as Secondary Variables ***Table 1-4***)
Academic Self Concept	Perception of self as academic
Academic Goal Orientation	Achieving academic knowledge and skills
Uncertainty Orientation	Able to take on new learning in an independent way - work in unfamiliar context
Values, Attitudes, Aptitudes	1 Empathetic: Collaborative / Concerned for Society / Academic Confidence 2 Agile: Enquiring / Creative and Enterprising / Open Minded / Risk Taking 3 Hard Working: Practice / Perseverance / Resilience

Table 1-4: *Definitions of Values, Attributes and Attitudes*

VAA variables	Definitions of Values, Attributes and Attitudes Competences
Collaborative	The ability to seek out opportunities to receive responses to your work, be willing to work in teams, able to evaluate your own ideas and contribution
Confident	A belief in your knowledge, understanding and action, recognising when you need to change your beliefs based on additional information, deal with new challenges including when it places you under stress
VAA variables	Definitions of Values, Attributes and Attitudes Competences **Continued**
Enquiring	The ability to be curious, willing to work alone, proactive, keen to learn, show independent thought, challenge assumptions, require evidence for assertions, move from absorption of knowledge and procedures to developing your own views and solutions
Creative/enterprising	Open minded and flexible thought processes, willing to innovate and invent new and multiple solutions to a problem or situation, adapt your approach according to need. Show originality in work, develop a personal style, be resourceful when presented a challenging task and problems, use you initiative
Open Minded	Take an objective view of different ideas, become receptive of the views and ideas of others- change ideas where there is compelling evidence
Risk –Taking	Experiment with novel ideas , speculate, work in unfamiliar contexts; avoid premature conclusions' tolerate uncertainty
Practice	Train, prepare, through repetition become proficient
Perseverance	The ability to keep going and not give up, even encountering obstacles and hurdles - persist to work to high quality and precision for a desired outcome
Resilience	The ability to overcome setbacks , remain confident, focused, and optimistic
Concern for Society	Self - explanatory

*Table 1-5: Learning Competences***.**

Learning Competences	
Meta-Thinking	Meta-cognition/ Self-Regulation/ Strategy
Realising	Intellectual Confidence/ Automaticity/ Speed / Accuracy

Table 1-6: Learning Competences – Definitions of Meta-Thinking and Realising Variables

Meta-Thinking Variable	Definitions of Meta-Thinking Variable
Meta-Thinking -	The ability to knowingly use a wide range of thinking approaches and to transfer knowledge from one circumstance to another
Realising Variables	Definitions of Realising Variables
Self-Regulation	The ability to monitor , evaluate and self-correct
Strategy	The ability to approach new learning experiences by actively attempting to connect them to existing knowledge or concepts and hence determine an appropriate way to think about work
Intellectual confidence	The ability to articulate knowledge and ideas based on evidence and where necessary defend them to others
Automaticity	The ability to use some skills with such ease that they no longer require active thinking
Speed and Accuracy	The ability to work with speed and accuracy

1.3 Summary – Literature Review

This Literature Review summarises the physics education landscape since the 1980s as one in which low uptake of physics persists compared to the other STEM subjects. It reviews the research in this area related to correlation studies of the factors which may contribute to the situation, to set as the context of the study. Then, pertinent to this research project it explores Learning Theory as defined by Illeris (2003) to set out the Dimensions of Learning as Content, Incentive and Interaction. The Content Dimension is dealt with as the Physics Competences in Chapter 2. The Incentive and Interaction Dimensions are defined through the work of Eyre (2016) and Hazari et al.(2010) as Learning Characteristics, Physics Identity and Learning Competences; in which the Learning Characteristics and Physics Identity form the Incentive Dimension, while the Learning Competences form the Interaction Dimension. The work of Eyre was chosen as the definitions and variables were considered by the author to map in a recognisable fashion to doing physics. This mapping is set out in Chapter 3.

Chapter 2 : Theoretical Framework

Chapter 2 is formed of two parts: Part 1:Deals with the theoretical framework for the Content Dimension of learning physics. Within this section educational Learning Competences are defined with reference to the demands of physics. These are Cognitive and Procedural Competences drawn mainly from the Advanced Cognitive Performance characteristics of Eyre's work and aligned with a set of Physics Competences compiled from authorities in physics in the UK, USA and the EU. Part2: Explores Physics Educational Research as a framework for data collection.

Part 1

Establishing this competency framework in relation to teaching physics, the Bologna Declaration of June 1999 and Tuning Committee (2008b) called for the establishment by 2010 of a coherent, compatible and competitive European Higher Education Area, which included the UK. Tuning Educational Structures in Europe started in 2000 as a project to link the political and educational objectives of those countries which had signed up to the Bologna Process for the higher educational sector. The Bologna Process required national governments, responsible for the education systems in their countries and individual universities, their associations and networks, to adhere to the process so that there would be convergence and parity across the European Union. Tuning is now globally adopted as an approach to curriculum development and evaluation of degree programmes. This improved the clarity and transferability of qualifications and enables the mobility of students. It defines competences for all subjects in relation to academic rigour and to meet employer demands as follows.

"*Competence represents a dynamic combination of cognitive and meta-cognitive skills, knowledge and understanding, interpersonal, intellectual and practical skills*…."

Competence as adopted by the Tuning Project conveys the meaning that a person is capable of a degree of preparation and sufficiency. Competences are understood to include 'knowing and understanding'. Therefore in education, sets of competences can be defined related to subject specific areas along with general academic competences such as, capacity to learn, analyse and synthesise. *This means that a person of competence has the capacity and ability to perform a task in a way that demonstrates a level of achievement. The person does not possess or lack competence in absolute terms but displays it to varying degrees along a continuum*. *(Tuning,* 2008)

Similarly the Organisation for Economic Cooperation and Development (OECD 2016) referred to competences in their Education Statistics. Since the OECD database is used for education research throughout the EU and worldwide comparative studies, this strengthens the case for an examination of physics learning by defining competences.

2.1 Competences

Educationalist Knud Illeris (2003) explains:

"*the modern concept of competence comprises not only relevant knowledge and skills, but also a range of personal qualities and the ability to perform adequately and flexibly in well-known and unknown situations. To be up-to-date, the concept of learning must be understood in the same broad sense, and therefore traditional learning theories must be revised."*

This idea of revising traditional learning is important, as the need to prepare young people for employment in the knowledge economy and in the near future integration of cyber space with physical space. The current Covid -19 pandemic has accelerated the advance of Technology Enhanced Learning (TEL) whereby deep learning, cognitive modeling and technology can converge and pathways to Personalized Learning emerge. A Competency Based Learning infrastructure could facilitate this, allowing students to work on specific competences which could help in attainment within certain areas or fields of physics and so mapping competences with curriculum and syllabus. In addition, 21st century teaching methods now address the cognitive and motivational state of the learner. Amy Ogan refers to the work of Johnson (2015) and Roll et al. (2011) in her online article on Precision Learning or Personalised Learning**.** She concludes that education is *"…no longer a "one-size-fits-all" approach in which everyone in a class sees the same material at the same time. (Ogan 2017)*

Using TEL, students working online will give rise to personalised data and learning footprints such that pupils, students and their teachers are enabled to assess their own learning needs. Knowing the exact competences needed to succeed at physics will allow them to develop strategies and measures to put in place for their personalised precision learning.

2.1.1 Cognitive Competences

Alan Van Heuvelen, a foremost physicist and educationalist, presented the Millikan Lecture to the American Association of Physics Teachers in 1999 in which he stressed the importance in physics education of Personal Learning Competences as described in Section 1.2.2 and Conceptual Physics Knowledge and Scientific Process Knowledge.(Van Heuvelen 2001)

Of the cognitive demand to acquire conceptual physics knowledge, referencing the work of others, Van Heuvelen used the words of Norman and Simon.

''*The powers of cognition come from abstraction and representation: the ability to represent perceptions, experiences, and thoughts in some medium other than that in which they have occurred, abstracted away from irrelevant details. This is the essence of intelligence, for if the representation and the processes are just right, then new experiences, insights, and creations can emerge.' Norman (1977)*

“Finding facilitating representations for almost any class of problem should be seen as a major intellectual achievement, one that is often greatly underestimated as a significant part of both problem solving efforts in science and efforts in instructional design.’’ Simon (1993)

In addition to the Learning Characteristics and Learning Competences defined by Eyre and set out in Section 1.2.2, Eyre also defines Advanced Cognitive Performance ACP characteristics. Based on this, it was the interpretation of the author that the work of Eyre would provide a useful basis for exploring some of the cognitive processes of physics learning. Hence Eyre’s definitions of Advanced Cognitive Performance (ACP) characteristics were applied here to the discipline of physics (Eyre 2016b).

This Advanced Cognitive Performance relates to the cognitive processing of Conceptual Physics Knowledge that Van Heuvelan points out as essential and important to physics; therefore in this study ACP are referred to as Cognitive Competences. Cognitive Competences are: Linking, Analysing and Creating. Table 2-1 shows these Competences and the variables they encompass, while Table 2-2 and Table 2-3 defines the variables.

Table 2-1: Advanced Cognitive Performance – Cognitive Competences

Cognitive Competences	Advanced Cognitive Performance Variables
Linking	Generalisation/ Connection Finding/ ‘Big Picture’ Thinking / Abstraction/ Imagination/ Seeing Alternative Perspectives
Analysing	Critical or Logical Thinking / Precision/ Complex and Multi-Step Problem Solving
Creating	Intellectual Playfulness/ Flexible Thinking / Fluent Thinking / Originality/ Evolutionary or Revolutionary Thinking

Table 2-2: ACP – Linking Competence and Variables

Linking Competence	Definitions of Linking Variables
Generalisation	The ability to see how what is happening in a particular instance could be extrapolated to other similar situations
Connection Finding	The ability to use past learning (knowledge and procedures) to seek possible generalisations
Abstraction	The ability to move from concrete to abstract thoughts
Imagination	The ability to represent the problem and its categorisation in relation to more extensive and interconnected prior knowledge
Alternative Perspective	The ability to take a range of views and deal with the complexity and ambiguity

Table 2-3: ACP – Analysing and Creating Competence and Variables

Analysing + Creating Competence	Definitions of Analysing and Creating Variables
Critical /Logical Thinking	The ability to deduct, hypothesise, reason and seek supporting evidence
Flexible Thinking	The ability to abandon one idea for a superior one or to generate multiple solutions
Fluent Thinking	The ability to generate ideas
Complex and Multi-stage problem solving	The ability to break down a task, decide on a suitable approach and then act
Evolutionary and Revolutionary Thinking	The ability to create new ideas by building on existing ideas or delivering from them
Intellectual Playfulness	The ability to recognise rules and bend them to create valid but new forms
Originality	The ability to conceive something entirely new
Precision	The ability to work effectively within the rules of a domain

As further argument on the application of Eyre's work to learning and doing physics, Eyre's work was derived from that of Bloom and others (Driver 1989; Driver and Easley 1978; Larkin 1983; Ibrahim, Buffler and Lubben 2009; Brown and Clement 1987; Champagne, Gunstone and Klopfer 1985; Oldham 1986). Creativity as described by Guildford (1967) and Torrance (1974); Critical Thinking by Scriven and Paul (1987); Precision and Originality by Bloom (1985); Abstraction by Pashler et al (2007) and Kolb (1984); and her own work on gifted and talented children.

Bloom's Taxonomy (1956) has influenced teaching and curriculum development of science for over fifty years. Revision by Anderson and Krathwohl (2001) and Marzano (2006) updated the Taxonomy, removing the hierarchy and taking into consideration the current education research and neuroscience developments of understanding brain development. The revised version by Anderson is given in Table 2-4. A good abridged version is given by Wilson (2013).

Table 2-4: Revised Bloom's Taxonomy

Anderson et al Revision of Bloom's Taxonomy	
Knowledge	Terminology/ Facts -- Conventions, Trends and Sequences, Classification and Categories, Criteria, Methodology: Abstractions, Generalisation, Theories & Structure
Comprehension	Verbal, Written, Symbolically, Experimentally –Translation, Interpretation, Extrapolation
Application	Bringing to bear on Knowledge or an Abstraction the appropriate generalisations or principles

Anderson et al Revision of Bloom’s Taxonomy Continued	
Analysis	Identification or classification of elements; relationships among elements ; organisation of principles which govern elements
Synthesis	The generation of new knowledge – unique communications: a plan or set of operations; a set of abstract relationships
Evaluation	Judgements appraising accuracy; effectiveness; economical; satisfying

2.1.2 Procedural Competences

Van Heuvelen (2001) also stresses the importance of Scientific Process Knowledge. In this study, this is placed under the heading of Procedural Competences, specific to the process of doing physics and to the Scientific Method.

Scientific Enquiry or Scientific Method was developed since the time of Aristotle around 347BC. An interesting historical account is given by John Losee (1980) but a contemporary definition at a level appropriate for secondary schools is given by Wenning (2006) wherein he provides a list of fundamental scientific enquiry competences as:

- Identify a problem to be investigated.
- Using induction, formulate a hypothesis or model incorporating logic and evidence.
- Using deduction, generate a prediction from the hypothesis or model.
- Design experimental procedures to test the prediction.
- Conduct a scientific experiment, observation or simulation to test the hypothesis or model.
- Collect meaningful data, organize and analyse data accurately and precisely.
- Apply numerical and statistical methods to numerical data to reach and support conclusions.
- Explain any unexpected results.
- Using available technology, report, displays, and defends the results of an investigation to audiences that might include professionals and technical experts.

2.2 Physics Competences

The next step was to show how and where these cognitive and procedural competences are specific to physics and so define a set of Physics Competences .

2.2.1 The Nature and Extent of Physics.

Physics is the science of fundamental concepts. Physicists need to understand concepts of fields, forces, radiation and particle structures which are interlinked to form complex models. Such models are used to explain the wide range of ideas from the development of the universe to the invention of the new technologies of the modern world (NOAA 2009). Physicists work with the concept of cause and effect, the phenomena of action at a distance, potential differences as drivers, proportionality and probability. They know what it is to experience and observe phenomena, execute different types of scientific enquiry, synthesize theories, articulate scientific concepts, analyse quantitatively and qualitatively through a developed curiosity. And thus the physicist must possess or acquire and develop many competences.

The Quality Assurance Agency for Higher Education (HEQAA) describe the “Nature and Extent of Physics” as:

“Physics is concerned with the observation, understanding and prediction of natural phenomena and the behaviour of fabricated systems. Physics is a continually evolving discipline that has theoretical, computational and experimental aspects; many physicists span these categories. It is characterised by the idea that systems can be understood by identifying a few key quantities, such as energy and momentum, and the universal principles that govern them.” HEQAA (2019)

This description of physics is important in this research because it supports the premise of the study in that it was not necessary to ask specific physics problem solving questions but rather accept that the population of physics learners, understanding the above, would draw on this in providing the research data related to doing physics and the physics competences therein.

2.2.2 The Physicist

Jon Ogborn, physicist and honorary fellow of the IOP describes physicists as:

“seeking out the most fundamental explanations that have utility and currency across many domains. They are not satisfied with superficial explanations. They apply systematic criticism to every idea and result. They have to bring to bear a wide range of knowledge to make sure each analysis is consistent with what is already known. They are forced to be very creative, always looking for new answers or new approaches” (IOP 2017a).

From this quote by Ogborn it can be summarised that Physics requires advanced levels of cognitive performance for thinking and reasoning towards understanding of phenomena and concepts, knowledge construction, knowledge transfer and problem solving. In addition meta-thinking, specific learning competences and behaviours are required to support this doing of physics. An IOP steering group (2014) has summarised the nature of physics and its demands in learning. These have also been described by Tracy (2018) as follows:

1. **The Characteristics of Physics Explanation**: aim to provide explanations that are the most fundamental, synthesising, unifying, consistent, simplified, economical, elegant and maybe counter-intuitive.

2. **Explanations by Practical Investigation**: are grounded in observation of phenomena and experimental measurements. These require procedural knowledge such as isolating phenomena, controlling variables, observing and measuring, analysing and interpreting data, testing plausibility of results, developing and refining explanations

3. **Thinking and Reasoning Explanations**: are developed from data using reason and logic, refined argument and critique and include deductive, inductive and probabilistic reasoning, geometric and algebraic proofs.

4. **Explanations by Mathematical Formulations:** in which some models result from powerful mathematical relationships between defined quantities by seeing and exploiting the power of mathematical formulations by using numerical techniques, computational thinking to define quantities and look for relationships : approximations, orders of magnitude, extreme case reasoning, operational definitions, algebraic reasoning, proportion and inverse proportion, ratio, compensation, change over time, rates, accumulation and exponential change . These mathematical models yield deep quantitative understanding that enables the physicist to make predictions that work universally.

5. **Knowing and Thinking with Physics Models:** many explanations are based on models with which to think and make predictions; simplifying situations, considering, using constituent parts and their properties, predicting behaviour .

6. **Cycles of Developing Physics Explanations**: which are durable and reliable because they are developed and tested through combinations of observation, reasoning, modelling, prediction and testing

All of the above had to be considered in the defining of Physics Competences.

2.2.3 Defining Physics Competences

An appropriate Physics Education Research goal is to find how students become *competent* in physics so that more effective instructional tools and techniques can be developed. The problem of low uptake in physics is experienced throughout most of the world and so whatever is produced in this research should seek to have the greatest level of relevance and readership. Therefore it was important to explore some internationally recognised benchmarks.

Niss and Hojgaard (2011) worked with the European educational definition of competence (as given in Section 2.1.1) in their development of mathematics teaching and learning criteria, for educational policy and curriculum development in Denmark, which received international interest. They refer to competence as the *mastery* of a subject and *levels of mastery* within it. This reference to mastery was also important in this research in relation to defining a scale of mastery for physics competences (Section 3.3).

Physics competences, like in mathematics, comprise having *knowledge of, understanding, doing, using and having an opinion about physics* (Niss and Hojgaard 2011) in a variety of contexts. Dolin makes use of the Niss mathematics competences in his PhD thesis to produce a parallel set of competences for physics (Dolin 2002), translated from Danish by Nilsen et al (2008). The Tuning Project (Tuning 2008a), based on work by the European Physics Education Network (EUPEN) defined Tuning physics competences to have three branches: Cognitive Abilities, Practical Skills and additional Generic Skills. The Tuning Physics Competences and Dolin's Physics Competences are compared in Table 2-5. Note that, in Tuning Physics Competences reference is to physics at Higher Education level, whereas Dolin competences are inclusive of both levels of education, secondary and tertiary.

Table 2-5: Comparison of the Tuning and Dolin Physics Competences

Physics Competences (Dolin)	**Physics Competences (Tuning)**
Perform Physics Thinking Perform Physics Reasoning	Theoretical Understanding Deep Learning
Build + Analyse Models	Modelling
	Problem Solving Mathematical Ability
Work with Different Representations of the same Phenomenon Communicating In, With, About Physics	Absolute Standards Awareness
Plan, Perform, Describe Experiments	Experimental Skills Estimation Skills

Seeking references to *Physics Competences* in UK education finds instead the terms and definitions of *Skills* and *Benchmarks*. Both tertiary and secondary education levels are influenced by the authority of the Institute of Physics, as the national body for the promotion of physics. The IOP definitions from the physics degree accreditation framework (IOP 2014) draw on the Higher Education Quality Assurance Agency Benchmarks (HEQAA 2019) and set levels for physics skills and learning achievement outcomes for undergraduates. At secondary level education the Department of Education and National Examination Boards for schools determine benchmarks for their individual syllabi for post 16 qualifications such as Advanced Secondary, (AS) and Advanced, (A) level examinations. The top three examination boards AQA, Edexcel and OCR as key examples for secondary level (IOP 2011b), (HEQAA 2019), (*AQA* 2017), Edexcel. (2015), (*OCR* 2018) respectively. The school level qualifications are set out as learning criteria, determined on the university entry requirements, they are derivatives of the IOP physics degree accreditation.

Comparing the UK and European Union to the approaches taken in the USA, triangulates current status between the three main regions in the Global North; which would look to each other as reference. The American National Research Council, (NRC) Education Committee has based the development of a curriculum framework for tertiary and secondary physics education on the concepts and core ideas of physics education research as a set of *Practices*, in effect competences; the coordination of both skills and knowledge simultaneously. Based on these Practices, at tertiary level, undergraduate physics courses are on a trajectory of change with the AAAS Project 2061 (A.A.A.S 2006) approved by the American Association of the Advancement of Science AAAS and the Anchors Project approved by the National Science Teachers Association in 2009. At secondary level the physics curriculum has been approved under the direction of the National Research Council (2012). Therefore Table 2-6 compares the definitions, benchmarks and practices of Physics for the UK and USA systems and are set out in five rows to match up in similarity to the five rows of Physics Competences of Dolin and Tuning, Table 2-5.

Table 2-6: Definitions, Benchmarks and Practices of Physics: UK and USA

Institute of Physics (UK) **Physics Skills and Transferable Skills (2014)**	**Higher Education Quality Assessment Authority (UK)** **Benchmarks(HEQAA 2019)**	**National Research Council (USA)** **Practices(2005)**
Analytical Skills Communicate complex information Construct logical arguments	To reason clearly, communicate complex ideas across disciplines. Creativity and imagination in using underlying principles.	Asking questions and defining problems. Engaging in argument from evidence
Use mathematics to describe the physical world. Compare results critically with predictions from theory.	Use theoretical models expressed in mathematical terms. Use mathematics to formulate theories and make predictions.	Developing and using models
Tackle problems in physics and formulate an appropriate solution. Formulate problems in precis terms Identify key issues Understand and interpret data precisely	Problem solving using reasoning. Problem solving using mathematical formulation and solution Understanding, Analytics and Prediction.	Constructing explanations and designing solutions
Compare results critically with predictions from theory Communicate complex information.	Communication of complex ideas. Judge statistical representations.	Using mathematics and computational thinking Analysing and interpreting data
Plan, execute and report the results of an experiment or investigation Create hypothesis Assess reliability of data Link numerical models to experiment of theory	Plan, execute and report on experimental investigation. Observation, Make measurements and validate when theory agrees with experiment. Analyse using large scale datasets.	Planning and carrying out investigations. Obtaining, evaluating, and communicating information

2.3 Summary – Part 1: Competences

This section has introduced the idea of a competency based learning for physics. It highlights the importance in meeting (a) the new capacity of Technology Enhanced Learning, (b) personalized learning, (c) an international education common approach and (d) the needs of employers. The current descriptions and definitions of the demands of doing physics have been compiled and identified as cognitive and procedural competences. European sources of the term Physics Competences, Tuning and Dolin were compared to descriptors for physics education used in the UK and USA.

Part 2

2.4 Physics Education Research

Physics Education Research (PER), is a discipline that emerged in the early 1980s. It refers to all aspects of physics education from curriculum development to the formation of cognition thinking and reasoning and knowledge transfer for physics. PER as an overarching domain is promoted by professional bodies such as the Institute Of Physics (IOP), American Institute of Physics (AIP), Tuning Physics and therefore this discipline is central to this research. The dimensions of PER and how they feature in this research as a framework are set out in this section. This framework enables a novel data collection. The scientific rigour of the approach is described and using an online questionnaire as a mode of investigation is justified.

PER has grown rapidly and extensively. Russ and Odden (2017) describe this expansion as “boundless and chaotic” and presented a very useful overview in which they describe six different dimensions of PER that are relevant to this study:

- Population
- Contextual
- Theoretical
- Conceptual
- Disciplinary
- Methodological

Until recently PER focused on any one of these dimensions. However outcomes suggest that trying to improve physics learning by adjusting one facet at a time does not have the desired result. Instead a multifaceted approach is needed. As an example, in their work on Critical Thinking, Tiruneh, DeCock and Elen (2018), point out: “*Despite the large body of research into Critical Thinking (CT) skills in physics and higher education, there is little consensus on how educators can best support the development of CT.”* They conclude that there are other factors that interplay and tackling any one factor is not sufficient.

Considering the motivation to learn in physics, Huber and Seidal (2018), taking a physics module on Electricity and Magnetism as their study, looked at the interplay of cognitive and motivational-affective student characteristics on attainment, to find that interplay between two or three factors is not sufficient. They conclude that the diversity of the interplay is significant.

Therefore no further literature review into the individual research dimensions was required but rather a strong indication that the approach taken in this research to look at the interplay of multiple factors and describe physics learning in a holistic fashion had merit.

This research study factored in all the dimensions in establishing learning and learner profiles of successful physics learners. Each dimension is explained below with consideration of how it was addressed in the data collection.

2.4.1 Population Dimension

Mainstream PER that seeks to influence physics education practice has been evaluating the constructs of physics education in school age and undergraduate students. This population is studied for a number of reasons. Strongest is the fact that, it is these young people that the research aims to help and it is for these young people that the education practice needs to be moulded. Secondly they are a captive population and so data collection is facilitated.

By contrast this research uses a new lens of research, namely data collection from a population of physics educated people in early, mid and late careers in physics and non-physics related employment. Hence the study audited an adult cohort which for the most part were away from schools and universities as seats of education, and so out of the context of physics learning. This meant that they can take an informed, retrospective view of their student self and reflect on their physics learning with the benefit of hindsight. This is a phenomenographic* approach. A phenomenographic analysis seeks a "*description, analysis, and understanding of . . . experiences*". The focus is on variation: variation in both the perceptions of the phenomenon, as experienced by the actor, and in the "*ways of seeing something*" as experienced and described by the researcher.

Phenomenographic analysis aims for a collective analysis of individual experiences as described by Greeno, Collins and Resnick (1996). Hence, this data collection can render both quantitative and qualitative results that can be related directly to teaching physics students. Assuming that the experience of the target population would be similar to any set of physics learners then it could be concluded that current students could benefit if the findings from the analysis are incorporated or addressed in delivery by a new pedagogy.

2.4.2 Contextual Dimension

Contextual Dimension covers two aspects; the micro and macro-systems of physics learning. A micro-system would involve studying students and, or teachers in the classroom or structured educational setting, whereas a macro-system would be used to explore patterns, at large, under the influence of culture, subcultures, economic, political or social systems. The micro-system is most often studied by subject observation whereas the macro-system uses interviews and surveys.

In most mainstream research, the students and teachers are in active physics learning environments (Section 2.5.1). Such studies are predominantly experiential and the procedure examines ways in which the teaching of physics could be improved by understanding the learning process of the students. The system therefore is a micro-system. The young people involved are required to relate to their learning and often required to verbalise their learning or be observed in learning (Reiss 2012) (Cheng. Y, Payn. and Witherspoon. S 1995).

The macro-system relates to the student as a learner and what shapes their learning; that is the external influences that weight the personal learning system. This is a difficult task as students may not be aware that their micro-system is strongly biased or influenced by their macro-system and the researcher cannot access or adequately know the macro-system for all students in their study.

Although the main focus of this research pivots at the senior secondary school student, the situation is similar in the case of studying physics undergraduates. These studies are also within the context of a subject specific, structured learning environment and so study a micro-system. With this set of more advanced learners who have chosen to study physics, it could be said that they are less likely to be influenced by any macro-system. Although this may be the case, another problem exists, research which has compared understanding of physics concepts between expert physicists and novice physicists (i.e. comparing university teachers to their undergraduate students), (Kuhn 1989) has shown significant differences in the reports and descriptions of understanding and learning for each group. This Novice - Expert dichotomy could be said to infer that the novice versus expert learner experience must be taken into consideration in analysis of data or that the learner needs to have a specific amount of physics experience in order to develop higher understanding, and so the two groups are not comparable and findings are compromised.

In this research, the target population, as holders of a physics qualification at senior school level, could answer questions by drawing to mind their knowledge of physics, the nature of physics and relate to their learning in a holistic way with the benefit of hindsight. In this way the research drew on a wealth of learning experience that was mined, distilled and refined by the reflective self-assessment of the participants. It examined both the micro and macro systems. The micro-system as the reflection of the individuals on their classroom experiences and their learning in that environment and the associated context. A macro-system with the context of the education era, external systems such as the curriculum and examinations of the time and their personal backgrounds. It is also a macro-system of a large disparate population in terms of demographics.

2.4.3 Theoretical and Conceptual Dimensions

The ultimate goal in the study of physics is to enable students to understand the theories and concepts of physics. These dimensions within Physics Education Research are necessarily subject specific, such as quantum mechanics, thermodynamics, and electromagnetism. However the decades of research have shown that cognitive studies in these areas and any recommendations for pedagogy improvement, acted on alone, do not result in the desired effect of greater understanding and learning in physics and more people studying physics (Ryan, Deci and Edward 2000).

It is important to note this finding as it adds further strength to the multi-faceted approach taken in this study. Most important however is that these Theoretical and Conceptual dimensions have been set as the background and ground level in the study but not referenced to or itemised specifically.

This was the case for two reasons. Firstly, since all respondents were volunteers it was important that they would not feel stressed by needing to attempt any physics problem solving questions or exposed in any limitations of their conceptual knowledge of physics, since for many, their direct use of physics may be years in the past. There was also the matter of use of peoples' time. Problem solving or searching questions about understanding physics would be very time consuming and therefore deemed inappropriate to ask of the volunteers. Secondly, the development of a scale of mastery with four specific levels would assess the participants' mastery of the physics competences by including questions on the theoretical and conceptual thinking and reasoning competences of the discipline of physics as a whole. In answering such questions it is expected that each respondent would be drawing on their own recollections of physics theories and conceptual models they dealt with in the past, and their sustained physics knowledge, as they examine their thinking and reasoning processing and strategies. In this way, with a larger number of returns from the large population of respondents, the questionnaire would provide information founded on a significant breadth of physics for the theoretical and conceptual dimensions. The collective result from all participants would form a record of the diversity of attainment in learning in these dimensions and so generic profiles of these dimensions of 'doing physics' would be described.

2.4.4 Disciplinary Dimension:

When physicists talk about their discipline in physics, be it quantum mechanics, electromagnetism or any other, then they communicate to each other with reference to ways of thinking and reasoning in understanding and problem solving related to that area of physics, the related concept formation and knowledge transfer. Van Heuvelan (2001), Gire and Manague (2010) Etkina (2015) lead among the many who have researched the epistemological perspectives of student's personal learning practices.

These researchers operate often as teacher-researchers. Through their own understanding of physics concepts and learning expertise they decipher the learning process with students, mainly at undergraduate level. Roth, (1995) in his research of Knowing and Learning in Open Inquiry Science in school based learning also describes his research as the findings of the teacher-researcher. Roth makes use of Habermas' (1971) Theory of Cognitive Interests as a framework to explain these teacher-researcher developed theories of practice. In this study the respondents' physics competences and their self-assessment of their powers of thinking, reasoning and problem solving were recorded through the use of lists of direct and indirect questions on concept formation and knowledge transfer.

2.4.5 Methodological Dimensions: Mixed Method Approach

Physics Education Research uses both qualitative and quantitative methods and often mixed methods. The choice depends on the type of study and often the origin of the research, whether it was part of Education, Cognition or Physics Education research. In this study the use of online data collection by questionnaire allowed elements of both qualitative and quantitative research. The qualitative element allows the complexity of physics learning to be revealed. While employing the quantitative element means that complex constructs or variables can be quantified by a process of operationalisation. Thus the complexity can be reduced by statistical analysis. (Braun 2013; Creswell 2014b)

2.5 Scientific Framework

Assessing the future of Physics Education Research, Lillian McDermott observed that:

"*Unless we are willing to apply the same rigorous standards of scholarship to issues related to learning and teaching that we regularly apply in more traditional research, the present situation in physics education is unlikely to change*." (McDermott, 1998)

With this consideration, the research framework sought for scientific rigour and so followed the advice of Greg Schraw in the proceedings of the Physics Education Research Conference. Schraw (1998) to compare the three quantitative research frameworks: True Experimental, Quasi-Experimental and Correlational.

Schraw made the case that "*quasi-experiments are probably the ideal study, particularly in terms of physics or science education research*". This is because the quasi-experimental frame allows control of variables while in a live setting so that findings can be generalised in a meaningful way. As such the data would be collected with the following criteria:

Random Selection and Random Assignment The population of respondents were collected through social media and from physics related networks so it was representative of physics learners but perhaps a limitation of the study as a self-selecting group.

It could be considered that this group of respondents had an above average interest in physics education, however this was considered to be a positive attribute in that their approach to the survey would be thorough. Also the questionnaire introduction referred to ‘success in physics’ so that self-selection may account for the high proportion of high achievers and graduate level respondents and again this could be considered a limitation. At the outset, it was recognised that should biases become apparent at the data cleaning stage, then using the demographics and staged sampling of the large population, equivalent group sizes could be achieved for analysis. In summary the data collection was not a random selection.

Independent Variables. The variables were controlled. In this case the population has a threshold of physics learning to senior level in secondary school, e.g. A level, such that physics knowledge and sufficient physics learning are fixed

Manipulated Dependent Variable. These are the constructs which were measured: Physics Competences and Physics Identity; Learning Characteristics and Learning Competences.

True Control Group. A group who have A level physics and then STEM education compared to a group with A level physics and a Physics Degree.

Statistical Controls. Checks were carried out on the collected data to reduce within group variability. To ensure this statistical significance was achieved, data demographics would be checked throughout the collection period.

Pre-tests. The questionnaire would be tested out in a number of pilot studies checking validity and reliability and accounting for evolution of the data collection.

2.5.1 Comparable Studies – Learning Physics and Research Methods

In establishing how this research study would differ from others, examples were chosen from PER, as set out in the summary Table 2-7. Inclusion criteria were:

- An Interactive style programme within the last two decades.
- Related to or involving secondary school students of physics.
- Measuring multiple characteristics and their individual or interplay impact on the study of physics.
- Using the term competence or other terms of learning characteristics.
- Use similar methodology to this study to allow comparison.

The following were excluded:

- Research from national and international data sets –i.e. statistical studies.
- All studies on the challenges to studying physics – gender, socio-economic, etc. for which these are the main focus of the study and were not as seen from the view of the students who may not be aware in real-time of issues around their gender or their socio-economic status.
- Studies on undergraduates and curriculum development.
- Studies on conceptual understanding or any single perspective.

All information has been taken directly as quoted or paraphrased from the referenced website entry or research paper. Entries of Physics Education Research were included from the year 2000 to date. The main features are as follows:

- Research on attainment in physics, mainly with undergraduate groups and secondary school pupils.
- Within this the main focus at undergraduate level is with conceptual understanding and problem solving.
- With school pupils age 10-16 years focused more generally on attitudes to science, understanding of the nature of science and career aspirations.
- Research with post graduates focused on the 6 months to 5 year post qualification period and relates to career direction and skills and transferable competencies needed for employability or notable in physicists.

All these groups were the targets of research as they are immediately accessible and yield information and metrics that produce an immediate picture of the status quo. This is useful to monitor progress and measure the impact of various initiatives. Generally the findings are related to the context of international comparisons of attainment and factors such as socio-economic, gender, cultural differences and attitudes to science as distilled from the PISA and OECD data.

This review of the literature revealed no studies that investigated the cognitive, procedural and learning competencies and learning behaviours of doing physics as owned by a physics qualified population and therefore it appears that no studies have addressed the aims and proposed outcomes of this research.

Table 2-7: PER for Secondary School Students and Undergraduates.

Education Research STEM/Physics – Uptake/Engagement/Understanding/Competences
TISME (Archer and Tomei 2013) (Archer *et al.* 2020)
10-14years, 2009-2013, Kings College - 10-19 years, 2017 -2020, Institute. of Education. University. College, London Context : UK School based interviews and questionnaires on pupil's view and aspiration about science and science careers Focus: To understand the changing influences of the family, school, careers education and social identities and inequalities on young people's science and career aspirations.

EpiSTEMe Effecting Principled Improvement in STEM Education (Ruthven *et al.* 2013)

11-14years, 2008-2013, Kings College London

Context : UK School based student observation, interviews towards developing classroom resources and teacher CPD for intervention. Pedagogy – interactive and adaptive teaching methods to improve conceptual understanding and develop critical thinking

Focus: Student Engagement and Learning redesigned key aspects of physical science and mathematics teaching and learning so developing a principled approach to engage students and guide them towards understanding. Concerned with conceptual growth, identity formation, classroom dialogue, collaborative learning, and relations between every day and formal understanding.

UPMAP Understanding Participation rates in post-16 Mathematics And Physics (Mujtaba and Reiss 2013)

16-18years, 2008-2013, University of Cambridge

Context : Mixed Methods - qualitative and quantitative methods. UK schools based study. Measured physics and math proficiency , attitudes and recognition of learning

Focus : To determine the range of factors (individual, school and out-of-school, including home), and their interactions, that influence post-16 participation in mathematics and physics in the UK and to assess their relative importance among different student populations.

HOPE Horizons in Physics Education (*HOPE: Horizons in Physics Education 2013-2016* 2016)

17-19 years, 2013-2016, Erasmus Project UK, Europe, North and South America , India

Context: Questionnaires and interviews with senior secondary school students from the most academic, high attainment groups and undergraduates.

Focus : Attitudes of senior school students about choosing to study physics.

Like our research – looked for the success factors in students and undergrads in choosing physics- the internal and external motivation. Also assessed the Tuning competencies and competencies for innovation and entrepreneurship.

Stimulating Physics (IOP 2018)

11-18years, 2013- ongoing

Context: Whole school culture intervention- looking at gender biases in six subjects and addressing changes to culture. pilot study with London schools – expanded to phase 2 with Ambassadors and direct interaction with girls in physics

Focus : This work started as enrichment in physics and research into low uptake and retention of girls in physics. Now working with Gender Balance Officers to address issues of gender balance in the whole school culture.

Skills Required by New Physics Graduates (Overton and Hanson 2010)

22-23years , 2007, The Higher Education Academy /UK Physical Sciences Centre

Context : UK university alumni 2.5yrs post- graduation

Focus: Uses the Tuning list of competences and lists of physics subject knowledge to compare how much physics knowledge and Tuning competency skills, acquired at university, were used in the workplace and so assessing employability and work readiness but also evaluating which skills and competences come to the workplace through physics

.

TIMMS Trends in Mathematics and Science Study

(Niss and Hojgaard 2011; Dolin 2002; Nilsen, Angel. C and Gronmo. L.S 2008)

17-19years, 1995 -2008, Teacher Education and School Research, University of Oslo

Context: Senior school students carrying out physics problems with and without mathematics; international project involving Norway, Sweden, Russia and Slovenia.

Focus: Compares the competences of mathematics as defined by Niss (2003) with competences in Physics as defined by Dolin (2002), thus showing that the key mathematics competence for physics was handling symbols (algebra).

PRiSE Persistence Research in Science Education (Hazari *et al.* 2010)

16-19years, 2010, US high schools

Context : Senior school physics students in 34 randomly selected US high schools. Drawing data from the Persistence Research in Science and Engineering (PRiSE) project, which surveyed college students studying English nationally about their backgrounds, high school science experiences, and science attitudes. The study uses multiple regression to examine the responses of 3,829 students

Focus: This study explores how students' physics identities are shaped by their experiences in high school physics classes and by their career outcome expectations. The theoretical framework focuses on physics identity and includes the dimensions of student performance, competence, recognition by others, and interest. This study concluded that the measure for students' physics identity was found to strongly predict their intended choice of a physics career.

This study -Doing Physics

19 -75+, 2018-2021. Leeds University + Ogden Trust

Context: Mixed Methods- Questionnaire and interview with predominantly UK based STEM network members and via physics related social media routes.

Focus: Profiles of successful physicists at all levels to determine competencies to levels of mastery, motivation and engagement.

2.6 Mode of Investigation

Methods of data collection from human subjects include: Discussion Groups: Interviews: Face to Face Surveys: Individual Hard Copy Questionnaire or Online Questionnaire. Each of these methods were compared and contrasted as set out in Table 2-8. In conclusion, for reasons of balance of advantages against drawbacks the scope of the research and its aims were best addressed using a mixed methods approach and conducting data collection by online questionnaire. Data was collected by an online questionnaire platform (*OnLine Surveys (Formerly Bristol On Line)*) This platform was recommended for use by the University of Leeds.

Table 2-8: Criteria for Choosing a Format of Data Collection

Discussion Groups / Interview / Face to Face Survey	
Advantages	Drawbacks
• Free flow of useful information • Opportunity to receive very novel responses	• Open to distraction and tangents from key data. • Some participants may feel pressured, intimidated or worried about giving the right answer • Participants bias as they wish to please/impress the interviewer • Time consuming • Expensive • May require a lot of travel unless by social media • Time limited sessions may result in insufficient data • Time needed to transcribe responses for data analysis
Hard Copy Surveys	
Advantages	Drawbacks
• All the drawbacks listed above are negated	• Cost and time for producing and distributing hard copies • Very low returns – typically 4-16% • Time needed to transcribe responses for data analysis
Online	
Advantages	Drawbacks
• All the drawbacks of the above two categories are negated. • Target audience can be reached directly online by email invitation. Hence reach wide audiences through many existing STEM education stakeholders. Link targeting through social media channels- Twitter, Linked In and Facebook. • Some immediate data analysis provided from the online platform. • Data can be exported directly to Excel, SPSS and NVivo software analytical packages for analysis .	• The population is self-selecting. • A predominantly graduate level educated population responded. • The population were skewed towards the higher academic achievers.

2.7 Summary – Part 2: Instrument of Data Collection

This research considered the six dimensions of Physics Education Research (PER) as summarised by Russ and Odden (2017) in their review of the most recent two decades of studies. It is these six dimensions which define the theoretical framework of this novel, multifaceted and holistic study to reveal what it takes for success as a physics learner.

The study would collect data from an adult population as a macro system which examined physics education on a large scale. Physics concept formation, thinking and reasoning, problem solving and modelling, attainment, performance and the learning environment would all be measured indirectly by the reflective, self-assessment of the respondents. These personal learning retrospectives, with the benefit of hindsight would have the potential to properly identify the features of successful physics learning and the influences upon it.

Chapter 3 : Methodology and Method

This methodology explains the development of sets of Indicator statements which become the components of questions for data collection. Indicators are empirical statements that represent the variables to be measured. In this study they are expressed in layperson terms and phrases that would be recognised by a UK centric audience. The use of indicators allows a quantitative analysis of the data.

Since the aim of the research is to determine how students of physics are successful in the acquisition, assimilation, creation and elaboration of knowledge and understanding of physics it was necessary to define what this entails. In addition physics learners, as all learners, have a learners' self-system that enables and supports the processes of learning and doing physics.

This self-system and the processes of doing physics have been identified by the author as Constructs, broad, sometimes abstract concepts, and Competences. It was the work of the author to take generic constructs and competences as described by leading researchers and practitioners in education, cognition and physics, see Section 1.2.1 - 2.2.3 and summarised in *Table 3-1*, and apply them to the context of physics learning and physics learners. The resultant distillation and linking process was aided by the author's own physics knowledge and experience of doing physics through qualifications in physics, physics education and careers in application of physics.

Heron and Meltzer (2005) highlights the importance of physicists leading the research in physics education within physics departments for the most impactful and influential outcome that this accords. Such an outcome was sought in this research.

Table 3-1: Constructs and Competences.

Construct and Competences	Research relevant to this study.
Physics Identity Construct	The Physics Identity construct is defined based on the collective work of Bandara and others. (Hazari *et al.* 2010)
Learning Character Construct	Self-Determination Theory of Learning, Motivation, Values, Attribute and Attitudes. (Eyre 2016b) (Ryan, Deci and Edward 2000)
Advanced Cognitive Performance Competences	High Performance Learning and Advanced Cognitive Performance (Eyre 2016b)

Construct and Competences	Research relevant to this study. *Table 3-1* cont'd
Learning Competences	Taxonomy of Learning, Self-System, Cognition and Meta-Cognition of Bloom, Anderson and Marzano as described in Marzano (2006).
Physics Competences	Learning, Understanding and Doing Physics (Niss and Hojgaard 2011); (Dolin 2002); (IOP 2014); (HEQAA 2019)

Therefore the above Constructs and Competences needed to be applied and expressed in the context of physics and physics learning to form questions . This was achieved by a process of operationalisation as recommended for its relevance to physics by Abhilash and Vashti (2019).

Construct/Competences → Variable → Indicator → Question.

Besides allowing the data collection to be quantified, producing Indicators to create questions was an important factor in the quality of data. Respondents, gathered at large, would not be educationalists. Few would be within an education setting and non would have access to the researcher to ask for guidance or explanations. Therefore the situation required the researcher to provide a non-specialist lexicon and phrasing as the tools to enable respondents to express their learning effectively – that which they previously knew but had not needed to put into words.

> *"….sometimes it can be challenging and/or impossible to label, conceptualise, articulate and intentionally know what we know"* Koro-Ljungberg et al (2009)

Relating their personal learning is a phenomenographic* process in which responses drawn from the participants are reflective, informed, distilled and refined with the benefit of hindsight and expressed with the Indicators, as descriptive tools. The choice of indicator by respondents therefore, could be considered to equate to emic descriptions ('experience - near' concepts) that describe the meaning of their experiences of learning. The relationship could be shown as:

Constructs/Competences ⇄ Indicators ⇄ Respondents' Learning Experience

3.1 Competences, Constructs, Indicators

Physics Competences are dealt with separately in Section 3.2.

The Constructs and Competences of Table 3-1, namely Physics Identity, Learning Character, Learning Competences and Advanced Cognitive Performance Competences, as with any phenomena in physics, need to be reduced to sets of variables in order to be measured. In this case, the measurements are psychometrics and the variables are latent variables and must be further abstracted to a state of measureable outcomes called Indicators – representative of the Constructs and Competences.

3.1.1 Indicators

The variables which give rise to the indicators are tabulated in the Literature Review and Theoretical Framework, Chapters 1 and 2 and in tables from Table 1-1 to Table 2-4. The indicators were synthesised by the author as lead researcher. This single source authorship provided consistency, and validation was by a group of physics education researchers and other representative bodies as described in Section 3.6. The number of indicators per variable was dependent on the number of empirical statements required to completely describe the variable and the nuances within. In general the more nuanced variables required more indicators to capture a record of that variable from different perspectives, and as they may appear in different areas and disciplines of physics. All such indicators would therefore strengthen the validity of the measure. These Indicators appear as components in questions Q12, Q18-22 in the Questionnaire. Since these Indicators were created in this process of operationalisation (Abhilash and Vashti 2019) of established variables therefore the questions formed have been concurrently validated from peer reviewed established research.

3.1.2 Learning Competences and Constructs

Shown in Table 3-2 to Table 3-7 below, for each Competence and Construct, the variables are defined (blue highlighted cells) and the corresponding synthesised Indicators are listed. The number of indicators per variable varies, as discussed earlier, in the range of 13 for Motivation to 68 in Analysing. The percentage figures given for each, relate to the test of their validity as discussed later in Section 3.6

Table 3-2: Learning Competences – Indicators

Meta-Thinking	**%**
Meta-Thinking The ability to knowingly use a wide range of thinking approaches and to transfer knowledge from one circumstance to another	
Interconnect prior and new knowledge	92
Aware of your learning strategies - plan, evaluate, review iterations	67
Aware of scientific method and the nature of physics	67
Realising	%
Self-Regulation The ability to monitor , evaluate and self-correct	
Spot and Correct your own errors- accurate	100
Aware of strengths and weaknesses and adapting as needed	92
Methodical + systematic	83
Confident to work independently	83
Time management - keeping up the pace. i.e. Manage study time, revision and exam timing, assessing progress	75
Patience and persistence	75
Achievement motivated	67
Conscientious	67
Practice makes perfect	58
Took responsibility for your own learning - setting your own goals	58
Strategy The ability to approach new learning experiences by actively attempting to connect them to existing knowledge or concepts and hence determine an appropriate way to think about work	%
Interconnect prior and new knowledge	100
Apply scientific conventions	83
Good at recognising patterns in info, numbers, observations	83
Find an analogy as a starting point to frame your ideas	75
Apply numerical and geometric relations	75
Apply known ideas to complex imagined or theoretical situations	75
Determine the set of variable to be involved	75
Methodical	67
Question and seek evidence	67
Apply the iterative nature of building up understanding	58
Intellectual confidence The ability to articulate physics knowledge and ideas based on evidence and where necessary defend them to others	%
Able to defend your points/understanding	100
Able to present your ideas/solutions clearly and accurately	92
Produced clear conclusions	83
Able to spot your own errors,	75
Deal with complexity and ambiguity	75
Quietly confident in your abilities	75
Question and seek evidence	67

Automaticity Ability to use skills with ease that do not require active thinking	%
Good at recognising patterns in info, numbers, observations	92
Key physics principles come to mind unconsciously	83
Could do a number of stages or steps of a problem in your head	75
Know when you were on the right tracks	75
Good head for facts	75
Able to spot your own mistakes	67
You have a feel for numbers	67
You have an inherent talent for physics	67
Quick minded	67
Quick recall	67
You experience a flow of ideas	67
Much of what you needed to know seemed to just be there	58
You find physics intuitive -understanding phenomenon comes with ease	50
Speed and Accuracy The ability to work with speed and accuracy	%
Quick minded	92
Your work was accurate	92
Worked quickly through calculations	92
Able to spot your own errors	67

3.1.3 Learning Characteristics

Learning characteristics incorporate the Values, Attitudes and Aptitudes defined by Eyre and Academic Self Concept, Goal Orientation and Uncertainty Orientation as features of Internal and External Motivation.

Table 3-3: Values, Attitudes and Aptitudes – Indicators

Values Attitudes and Aptitudes	
Concerned for Society	%
It is important to you that physics could make the world a better place.	83
Like to help others understand physics	67
Values Attitudes and Aptitudes	

Collaborative Ability to seek out opportunities to receive responses to your work, willing to teamwork , able to evaluate your own ideas and contribution	%
For a topic or question difficult you, seek out someone to explain it to you	92
Talk physics outside lessons	75
Like to help others with physics	75
Make a key contribution to Q+A in lessons	75
Take part in physics Olympiad, clubs, competitions etc.	50
Be inspired and enthused by a role model	50
Confident A belief in your knowledge, understanding and action, recognising when you need to change your beliefs based on additional information, deal with new challenges including when it places you under stress	%
You can deal with the iterative nature of building understanding	75
Take an active role in discussion and debate of physics topics	75
Ready to take on new skills and approaches to improve your performance	75
Generally feel comfortable with each new topic	75
You source information beyond the syllabus	67
You were quiet in class but happy developing your own understanding	58
Set your own goals	58
Enquiring ability to be curious, willing to work alone, proactive, keen to learn, show independent thought, challenge assumptions, require evidence for assertions, move from absorption of knowledge and procedures to developing your own views and solutions	%
Curious/inquisitive	100
Active in classroom discussion and debate	92
Usually ask and answer questions	92
Question and seek evidence	92
Add information to classroom discussions, beyond the immediate syllabus	75
Want to know more about each topic, beyond needed for the syllabus	75
Read about science beyond course syllabus	75
Like to do science related experiments at school and outside school ,	67
Creative/enterprising Open minded and fle1ible thought processes, willing to innovate and invent new and multiple solutions to a problem or situation, adapt your approach according to need. Show originality in work, develop a personal style, be resourceful when presented a challenging task and problems, use you initiative	%
Enterprising –you were open to trying new ideas,	92
Innovative –you see interesting outcomes - Inventive - an idea's person	100
A problem solver	92
Liked a challenge - pioneering	67

Values Attitudes and Aptitudes	
Resourceful- you would find a way to do what it takes	83
Sometimes or often solved problems differently to others	75
Use your initiative	75
Open Minded Take an objective view of different ideas, become receptive of views and ideas of others- change ideas where compelling evidence	%
Question and seek evidence	83
Evaluate and draw on information with merit	83
Risk -Taking Experiment with novel ideas , speculate, work in unfamiliar contexts; avoid premature conclusions' tolerate uncertainty	%
Liked a challenge	92
Deal with complexity, ambiguity and uncertainty	83
Able to work in unfamiliar context	83
Generally felt comfortable with each new topic	67
Usually ask and answer questions (with reference to teenagers risking their image or fear of failing)	67
Liked to experiment at home or outside school lessons	50
Train, prepare , through repetition become proficient	%
Check back and re-evaluate your work	83
Tenacious	67
Consistently seeking ways to improve	67
Believed in practice makes perfect - do extra questions and work	67
The ability to keep going and not give up, even encountering obstacles and hurdles - persist to work to high quality and precision for a desired outcome	%
Patience and persistence	92
Often for difficult topics or questions you would stick with them for a long time to make progress	75
Determined to see a task through to the end	65
Conscientious	75
Systematic- like to order –produce tables/ranks	67
Work with accuracy to produce work of a high standard	50
Ability to overcome setbacks , remain confident, focused, and optimistic	%
Resilient to set back such as getting questions wrong	100
Cope with ups and downs of learning	100

Ability to overcome setbacks , remain confident, focused, and optimistic	%
Learn from your mistakes	92
Progress in spite of adversity	92
Seek help rather than give up	83
Deal with the uncertainty of success.	83
If topics or questions were difficult continue to work until progress is made	67

Table 3-4: Motivation – Indicators

Motivation - Both positive and negative motivations	**%**
Internal Motivation	
Self-motivated - such as you are determined to do well at physics or your studies	91
You experienced an inertia for doing physics	91
Took great pride in your physics knowledge.	82
Recognised yourself as a future scientist or engineer	73
Liked the accurate language of physics , scientific terms and formulae	73
Got a buzz out of physics	64
Academic/quirky/nerdy	54

External Motivation	%
Teacher pupil relations and other classmates -positive and negative	92
Whether you liked studying physics and how useful you considered it was to your plans	92
You liked to be rated as clever	75
Others viewed you as a definite scientist/engineer	75
Inspired+ enthuse by a role model	58
You took part in competitions, physics Olympiad, science and engineering clubs etc.	50

3.1.4 Physics Identity

Physics Identity has been defined by Potvin and Hazari (2013) based on the work of Carlone and Johnson in Science Identity. In simplest terms the Physics Identity is a proxy for a student's affinity towards physics – becoming a 'physics person'. Recognising that this identity can be external and internal it is the importance of the internal identity that may be strongest at supporting learning. This is the self-recognition, interest and performance and competence in doing physics as described by the Indicators of *Table 3-5*.

Table 3-5: Physics Identity – Indicators

Physics Identity	**%**
Perception of Ability to understand /perform Physics	%
Able to spot own errors in problem solving	100
Able to present your physics knowledge and ideas clearly- orally and written	100
Quietly confident in your abilities	92
Good head for science/mathematics/engineering/physics facts	83
Like to help others with physics	83
Others viewed you as a definite scientist/engineer/physicist	67
You have an inherent talent for physics	67
Good at abstract thought	67
Resilient to setbacks such as getting the answer wrong	67
Generally feel comfortable with each new physics topic in class	67
Take pride in your physics knowledge -good working knowledge	67
Recognise yourself as future scientist or engineer	67
Clever	58
You are an idea's person	50
You find physics intuitive	50
Much of the physics you needed to know was there in your mind	42
Enjoy the mathematical aspect of physics	83
Desire to learn more	**%**
Curious/inquisitive	100
You like how physics explained so much of everyday life	100
Enterprising –you were open to try things	83
Liked talking physics /mathematics/engineering	83
Physics Identity Continued	**%**

Desire to learn more	
You liked a challenge	83
Enjoy expanding on ideas and getting to grips with a new topic	83
Resourceful -can do attitude	75
Aware of your learning- had learning strategies	75
You get a buzz out of physics	75
It was important to you that physics could help make the world a better place	75
Interested in science and engineering	67
Self-motivated- set own goals	67
Like experiments at school and outside	67
Determined to see a task through to the end	67
Methodical	67
You believe in practice makes perfect	58
Love to study	58
Self-Efficacy : your belief in innate ability to achieve goals- will put in effort and overcome challenges	**%**
Like a challenge	75
Confident to work with minimal supervision	75
Able to defend your line of thinking	75
Determined to see a task through to end	75
Aware of your learning	67
Quietly confident in your abilities	67
Resourceful, you will find a way to do what it takes - can do	67
Resilient to setbacks such as getting questions wrong	67
Able to progress in spite of adversity	67
Recognise yourself as future scientist or engineer	58
Self-motivated	58
Consistently seeking ways to improve	50
You have an inherent talent for physics	42
Perception of recognition by others	**%**
Like to be good at physics because it is perceived as a hard subject	67
Like to talk physics outside physics lessons time	67
Indifferent to the perception of others	67
Academic/quirky/nerdy liked to be rated as clever	50

3.1.5 Advanced Cognitive Performance Competences

The ACP Competences, Linking , Analysing and Creating were explained in Section 2.1.1, and the variables are taken directly from definitions by Erye (2016b) to produce the indicators as listed in Table 3-6

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Table 3-6: Advanced Cognitive Performance – Indicators

Linking	**%**
Generalisation The ability to see how what is happening in a particular instance could be extrapolated to other similar situations	
Apply ideas to complex, imagined or theoretical situations	100
Take any statement about the individual object or event and generalise.	82
Imagine the object or event in 'ideal' conditions	73
Connection Finding The ability to use past learning (knowledge and procedures) to seek possible generalisations	%
Connect prior and new knowledge	100
Good at recognising links	100
Good at recognising patterns in info, numbers observations	100
Translate narrative questions into numerical form and apply formula,	73
Expanding ideas and getting to grips with new topics	73
Find an analogy as a starting point to frame the ideas	73
Produce clear conclusions,	64
Come up with new ideas to solve problems	64
Hypothesize	55
Apply appropriate skills, formula or conventions for the task,	55
Produce accurate/relevant diagrams to problem solve/ explain phenomena	55
Observant, making relevant and essential observations	36
Much of what you needed to know seemed to just be there,	27
Abstraction The ability to move from concrete to abstract thoughts	%
Good at abstract thought	100
Liked building mental mathematical and physical models,- i.e. See with your minds' eye	82
Change a narrative to mathematical form	82
Imagine the object or event in ideal conditions	64
Follow physics discourse	64
Good spatial awareness	36
Imagination The ability to represent the problem and its categorisation in relation to more extensive and interconnected prior knowledge	%
Usually come up with new ideas to solve a problem	82
Able to generalise for any individual event/system	82
Inventive	73
Imagine the object or event in ideal conditions.	55
Alternative Perspective The ability to take the views of others and deal with the complexity and ambiguity	%
Sometimes or often solved problems differently from others	82
Could usually come up with new ideas to solve a problem	82
Apply ideas to complex imagined or theoretical situations	73
Expanding ideas and getting to grips with new topics	55
You/others see you as a Blue Sky thinker creating compelling and original ideas	55

Table 3-7: Analysing and Creating – Indicators

Analysing + Creating	**%**
Critical /Logical Thinking The ability to deduct, hypothesise, reason and seek supporting evidence	%
Use observations, given facts/data induce explanatory principles/ premises	100
Analyse and validate data and theories	92
Deduce-conclude and reason from a set of ideas or theories	92
Translate a narrative into mathematical format and find a formula/ equation	83
Induce a general principle from a set of facts	83
Use logic to deduce a relationship	83
Able to make relevant and essential observations	83
Question or seek evidence	83
Make valid approximations	75
Create hypothesis	75
Draw clear conclusions	75
Problem solving	75
See things with the mind's eye- conceptual models	58
To be able to explain physics well	58
Flexible Thinking The ability to abandon one idea for a superior one or to generate multiple solutions	%
Explore alternative ideas or solutions	92
Could work with multiple ideas to find the best fit	92
Able to abandon one idea for a superior one	92
Resourceful – you would find a way to do what it takes to problem solve or design an experiment	75
Apply ideas to complex imagined or theoretical situations	67
You experience a flow of ideas	50
You find physics intuitive -you experience a flow of ideas	36
Fluent Thinking The ability to generate ideas	%
Fluent with ideas in problem solving	92
Enjoyed expanding ideas when getting to grips with a new topic	91
Able to build mental models	83
Apply ideas to complex imagined or theoretical situations	83
Explore alternative ideas or solutions to problems	83
Complex and Multi-stage problem solving The ability to break down a task, decide on a suitable approach and then act	%
Good at recognising patterns in info, numbers, observations	100
Change a narrative into numerical form	91
Apply ideas to complex, imagined or theoretical situations	91
Simplify complex and abstract phenomena to get to a set of parameters and relationships of a concept or theory	91
Interconnect prior and new knowledge	83
Could work with multiple ideas to find the best fit	81
Enjoyed working in an iterative way with mathematics	73
Liked the iterative nature of building understanding	73
Able to build mental models - see with the mind's eye	73
You could complete a number of steps in your head	64
You have an inherent talent for physics	36

Analysing and Creating continued	
Evolutionary and Revolutionary Thinking The ability to create new ideas by building on existing ideas or delivering from them	%
Able to envisage a solution to a problem	81
Inventive	81
Interconnect prior and new knowledge	81
To see the big picture	81
Explore alternative ideas or solutions to problems	73
Combine or rework equations to suit new situations and context	73
Enjoy expanding on ideas to get to grips with a new topic	67
Create hypotheses	64
Evolutionary and Revolutionary Thinking The ability to create new ideas by building on existing ideas or delivering from them	%
An ideas' person	64
Like to build mental models	64
Apply ideas to complex or imagined situations	54
Able to deal with complexity and ambiguity	45
Modify experiment to minimise uncertainty or improve reliability	45
Good at abstract thought	45
Intellectual Playfulness The ability to recognise rules and bend them to create valid but new forms	%
Able to rework equation to fit new situations	100
Explored alternative ideas or solutions,	75
Loved working with equation and formulae	58
You/others consider you to be a Blue Sky thinker creating compelling and original ideas	58
Originality The ability to conceive something entirely new	%
Sometimes or often you would solve problems differently to others	92
You are an ideas' person	92
Come up with original ideas	83
Inventive	75
You or others recognise you as a Blue Sky thinker	58
Precision The ability to work effectively within the rules of a domain	%
Apply scientific conventions	100
You work with accuracy	92
Select appropriate skills and conventions for the task	83
Methodical	75
Control parameters and variables - fair test	67
Observant - make relevant and essential observation	58
Like the iterative nature of building understanding	50
Enjoy working in iterative way with mathematics	42

Summary - Competences, Constructs, Indicators

Sets of Indicator statements which become the components of questions for data collection were developed. These Indicators are empirical statements which allow the Constructs and Competences of the Physics Learner to be expressed, thus allowing respondents to communicate their learning and performance of doing physics and enabling the production of quantative data for analysis of a complex inter-related learning system

These Constructs and Competences are the Learning Characteristics, Physics Identity, Learning Competences and Advanced Cognitive Performance Competences that had been identified from literature review. It was the work of this study to identify the Constructs and Competences and interpret them for the learning, understanding and doing of physics as well as matching them with a set of variables from which Indicators statements could be created. The process of operationalisation was explained and lists of the Indicators produced were tabulated .

3.2 Physics Competences and Indicators

This study aimed to collate all definitions, benchmarks and practices of physics, Section 2.2, to distil a concise set of Physics Competences and describe them by Indicator statements for use in data collection and also as an outcome of the study. These Competences and Indicators would allow educators, students, assessors and employers to have a common language and understanding of the processes of physics. To extend the use of the Indicators, and further as an outcome of the study, a response scale would be developed to describe levels of mastery of these competences, Section 3.3. Hence allowing for the formation of a competency profile for the learning and doing of physics (Wright and Masters 1982). This section describes how five Physics Competences were compiled and the synthesis of 46 Indicators.

The compilation process started by researching the use of the term physics competence. It was found in two European sources, Dolin (2002) and Tuning (2008a). Table 2-5 lists the Dolin and Tuning Physics Competences and shows the similarities for each; which totalled to five different competences.

By comparison, Table 2-6 showed that in the UK and USA the terms Definitions, Benchmarks and Practices of Physics were used. These Definitions, Benchmarks and Practices were set out in five rows to match up in similarity to the five rows of European Physics Competences of Table 2-5.

It was the work of this research study that by a process of collation, concatenation and cross referencing of these existing frameworks and definitions of physics, a set of five Physics Competences were thus defined as: Representation, Experimental Investigation, Problem Solving, Thinking + Reasoning and Modelling.

These competences apply across all areas of physics. They are not mutually exclusive but interactive and interdependent and represent a unified view to be used to further investigate mastery of the Theoretical, Computational and Experimental aspects of physics.

For the use of this set of 5 physics competences, the following 3 criteria are assumed:

- **Subject knowledge in physics and mathematics**: That the study participants have sufficient subject knowledge, hence the threshold entry point of a qualification of A level physics. Participants have a similar level of proficiency in mathematics: Trigonometry, Calculus, Probability, Vectors, Approximations, Numerical Manipulation, Dimensions
- **Knowledge of the nature of the subject**
- **Interest in Physics**

The Physics Competences are set out in Table 3-8 with the codes which represent each competence in the tables and figures of the Results chapters.

Table 3-8: The Five Physics Competences Elucidated in this Research.

Physics Competences		Code
Representation	Work with different Representations of the same phenomenon in the communication of Physics	R
Experimental Investigation	Plan, Perform and Describe Experiments	E
Problem Solving	Problem Solve	P
Thinking + Reasoning	Thinking and Reasoning	T
Modelling	Abstraction, Conception, Visualisation and Prediction	M

3.2.1 Variables

Physics competences need to be understood in terms of the cognitive demands they make on students' learning of physics. These demands include building conceptual structures, applying cognitive processes as cognitive competences and integrating with cognitive/procedural competences to problem solve and model (Van Heuvelen 1991). The structures and processes can be identified as sets of variables described from the sources of key physics educational stakeholders described below and listed in Table *3-9*, drawn from different areas of research and applied to physics. It is the unification of all these sources and the variables, which the author identified as belonging to each of the five competences, that lead to the creation of the set of Indicators used in the questionnaire for Questions 13-17. These Indicators describe the doing of physics across all areas and disciplines of physics.

Van Heuvelen (1991) identified the key '*characteristics of mind'* that students need in order to acquire physics knowledge and skills as: A*bstraction and Representation: the ability to represent perceptions, experiences, and thoughts in some medium other than that in which they have occurred, abstracted away from irrelevant details.*

Duschl (2008) conceptualised the nature of science learning into Domains of Inquiry. He defined a Conceptual Domain as scientific reasoning and an Epistemic Domain as the generation, development and evaluation of scientific knowledge, which entails the practices of collecting, evaluating and interpreting evidence. Furtak et al.(2012) defined a Procedural Domain which describes the methods or heuristics of discovery. That is asking scientifically oriented questions, designing experiments, executing procedures, and creating data representations.

This Abstraction and Representation, Inquiry and Procedural Domains of Inquiry parallel the concepts of Knowledge Construction and Knowledge Transfer as described by Eyre in terms of Advanced Cognitive Performance ACP (Eyre 2016b; Eyre 2007). Eyre categorises ACP as Linking, Analysing, Creating and Realising as dealt with in Section 1.2.2 and in Part 1, Chapter 2.

These sources are summarised in Table 3-9.

Table 3-9: Competence Variables as Sourced from Literature

Source	Variables
Van Heuvelen (1991)	Abstraction, Representation
Duschl (2008)	Reasoning, Generation, Development and Evaluation of Scientific Knowledge.
Furtak et al.(2012)	Asking Questions, Designing Experiments, Executing Procedures and Creating Data Representations.
IOP(2014) Definitions of Physics	Observation, Numerical Techniques, Evaluating, Interpreting, Simplifying.
Eyre (2016)	Linking, Analysing, Creating, Realising.

3.2.2 Indicators

Using these variables, their definitions and with the author's professional understanding of the demands of physics, each was further deciphered, subdivided and described by sets of indicator statements synthesised and listed in Table 3-10.

The number of indicators for each competence varied and occurred through the consideration for the comprehensive coverage of the different domains and fields of physics.

These Indicators as measures of the physics competences were validated as they concur with literature as described above and also through the work of Furtak et al (2012). Furtak and her team conducted a meta-analysis of 1625 studies into science learning; sourced on Web of Science and ERIC. With exploration of these 1625 studies on key terms of scientific method and inquiry, the team produced a list of 13 statements comparable to 13 of the indicators created in this study. These key statements were: Drawing on/Connecting to Prior Knowledge, Asking Scientifically Oriented Questions, Providing Conceptually Oriented Feedback, Generating and Revising Theories, Eliciting ideas, Mental Models, Drawing Conclusions based on Evidence, Arguing /Debating Scientific Ideas, Experimental Design, Executing Scientific Procedures, Recording Data and Representing Data. Hence this number of the indicators were concurrently validated.

Through the validation process, described in Section 3.6, the remaining indicators were refined and reduced in number to a final total of 46 as shown in Table 3-10.

Table 3-10: Physics Competences and Indicators

	Representation
R1	Use technical and scientific language
R2	Work with approximation, orders of magnitude, proportion, rates, exponentials
R3	Define phenomena in relevant physics terms
R4	Apply scientific method and conventions
R5	Search for and understand information about concepts.
R6	Understand and explain phenomena represented as a diagrams, graphs, tables or in a mathematical form
R7	Communicate data and physics concepts as diagrams, graphs, tables or in a mathematical form
	Experimental Investigation
E1	Identify phenomenon or physical properties involved
E2	Determine a set of variables to control
E3	Modify, adapt standard methods and procedures to detect, identify, quantify
E4	Accurately observe and measure
E5	Determine the reliability and plausibility of results
E6	Analyse and Interpret data
E7	Develop and refine conclusions
E8	Understand the relationship between theory and experiment i.e. design experiments from theory or apply physics theory to experiments

	Problem Solving
P1	Distil a problem to its basic elements
P2	Break down abstract and complex problems into multiple stages
P3	Ask relevant questions, identify patterns and relationships
P4	Create new ways of framing a problem or phenomenon
P5	Explain abstract, theoretical situations or models
P6	Translate a narrative into mathematical form
P7	Apply geometrics and algebraic proofs
P8	Explore alternative ideas or solutions to problems
P9	Combine or rework equations to suit new situations and context
	Thinking and Reasoning
T1	Understand the nature of physics: axioms, theories, principles and conventions
T2	Draw on prior knowledge relevant to the task or phenomenon
T3	Interconnect prior and new knowledge
T4	Take any statement about the individual object or event and generalise.
T5	Imagine the object or event in 'ideal' conditions
T6	Apply probabilistic reasoning
T7	Apply known principles to complex, imagined or theoretical situations
T8	Develop compelling ideas and hypotheses
T9	Deduce - reason from a general principle to a special case
T10	Induce - reason from a number of special cases to a general principle
T11	Defend your ideas /premise by constructing logical arguments
	Modelling
M1	Distil complex + abstract phenomena to a set of parameters and relationships
M2	Produce a mental representation or conceptual model - thought experiments
M3	Visualisation of data - mentally organise and process
M4	Interpret prior learning and experience for new situations
M5	Use logic to deduce a relationship
M6	Come up with relevant original ideas for explaining, measuring, predicting
M7	Develop descriptive models to understand complex systems
M8	Create a mathematical model that describes the phenomenon or problem
M9	Interpret and contextualise mathematical descriptions of physical phenomena
M10	Use constituent parts to predict behaviour
M11	Combine the process of evaluation and adaptation to observations, reasoning, induction, deduction modelling, prediction and testing

3.3 Scale of Mastery

Questions Q13-17 relating to Physics Competence differ from other questions in the study, in that they were answered using a four point response scale of the level of challenge each respondent would associate with each indicator. In this way a level of mastery of physics could be assigned.

In choosing a response scale the Likert Scale was considered but this was ruled out for the reasons discussed here. Using a Likert Scale would have required terms relating to Easy or Hard for each competence. These are subjective terms – considering a competence or concept to be hard or easy is relative to ability or experience or prior learning. Taking each indicator statement of a competence, it may be done with ease or need instruction to do it. A relatively easy competence or a relatively hard competence could be mastered. Therefore Likert terms would not have provided true measures of scale.

Likert Scales are symmetrical and bipolar and force the responses into equal weighting which distorts the data. In the case of odd number of choices (e.g. 3, 5, 7) they are prone to *acquiescent bias.* This means that should there is any indecision, the candidate chooses the central ground (Douven 2018). Likert also suffer from *social desirability bias;* where the candidate feels they should choose the most desirable response (Uebersax 2006). On these accounts the Likert scale was not a suitable option.

An alternate option was sought, one with which the scoring would be most relevant to the indicator statements and make the most sense to the respondents. Unless a person attempting to succeed in physics gives up, it cannot be said that a given indicator is unachievable.

Therefore the scale was defined at four levels according to each participant's self-assessment of their ability to have achieved each indicator at secondary level as:

Ease – With ease, could be achieved with ease

Effort – With typical level of effort, could be achieved with the typical amount of effort, comparable to peers

Guidance – With some guidance, required further instruction from the teacher or peers

Challenge – Challenging, in spite of extra instruction the participant had still not attained a level of mastery they were satisfied with.

In this way a scale which gives reference to levels of ease and effort could be taken as some measure of mastery. The four point scale was presented to participants to choose if they did/achieved each competence indicator according to the scale levels as demonstrated in Table 3-11:

Table 3-11: Four Point Scale of Mastery

Physics Competence Indicator	With Ease	With typical level of Effort	With Some Guidance	Challenging
Indicator 1	x			
Indicator 2 etc.		x		

An initial pilot trial questionnaire had used the term 'Too Challenging' but this was changed to 'Challenging' as it was gauged that desirability bias may explain the avoidance of this choice by the participants of the pilot; possibly viewed as an admission of failure.

Using the response scale above, it was reasonable to accept that the four options are not of equal intervals, non- linear, as the responses are subjective self-assessments and the purpose of the data analysis was to develop this ordinal scale to a calibrated scale. A very able and/or experienced physic learner may do any of the given competences with ease. Similarly one would expect that some respondents would find some competences challenging. It may be expected that the option 'With typical effort' to be the most common response.

With a large population of respondents it would therefore be expected that the outcome would be a *scale proper* and the scale units would emerge from the collected data. Such a scale is therefore calibrated by the population it has surveyed. It is important to reiterate that the scale is based on self-assessment of achievement and performance with reference to the participants classroom experience and hence this encompasses a spectrum of interpretation of the levels, however the large population size was important in this respect and this spectrum of interpretation lies within the calibration factor.

3.4 Summary – Physics Competences

From the literature review the disparate definitions and descriptions of physics and its associated processes and operations were distilled into a set of five core, concise and unifying Physics Competences. It was the work of this research to compile these Competences and match them with variables, identified from literature and therefore concurrently validated. The author created 46 Indicators by a process of abstraction and sub division of the variables. The 46 indicator statements describe the processes of physics in everyday language, accessible to all stakeholders to allow a common understanding and conversation. Furthermore a four point scale of mastery was proposed to allow assessment of Physics Competences. The scale would require respondents to rate their mastery of the Physics Competences according to their ability to perform them with Ease, a typical level of Effort, with some Guidance or had they experienced Challenge.

3.5 Phenomemographic Analysis

Chapter 8 gives the results for the narrative questions 19a, 21a and 21b, which explored the factors which may enhance or detract from physics learning. The responses to these questions required a phenomenographic analysis. This methodology and its method are explained here.

Phenomenographic analysis sorts perceptions and the process is that of iterations and comparisons of narrative until specific 'categories of description' emerge as the primary outcomes. This analysis is whole group orientated since all data is analysed together with the aim of identifying possible conceptions of experience related to the phenomenon under investigation, rather than the individual experiences. The object being not the phenomenon per se but the relationship between the participants and the phenomenon. (Braun 2013)

NVivo qualitative analysis software (QRS. International 2019) was used for this process and so the 'categories of description' are referred to here as Codes. The data was imported as excel spreadsheets into the software package. Auto-coding, as provided by the software did not provide a satisfactory outcome as too many unrelated codes were created. Therefore the iterative process was devised as a coding system which could be validated as part of its refinement process. The process involved the lead researcher and the two co–researchers in the following steps.

Step 1: Researcher 1 examined all the responses for each question and decided on a set of codes and their descriptions. The decision on what constituted a code occurred most often from the frequency of certain specific responses and key terms offered by the respondents, such that themes emerged directly and clearly from the data. These emergent themes are the research outcomes and the codes and the exercise of coding served to sharpen and quantify the analysis. In such a process there may be a subjective element and hence the codes had to be validated.

Step 2: As a means of validation, Researcher 2 and 3 chose the first 50-120 responses of each question and independently coded this sample.

Step 3: All three researchers discussed the themes that had emerged and the variance and merits of the codes. Researcher 1 drew up tables of comparison for all codes produced by each researcher. By equating like codes within the sets and then considering themes, clarity and code brevity, the penultimate sets of succinct and apt codes were determined as sets of draft codes .

The themes were: Minorities, Challenges and Heuristic Learning. Good agreement of greater than 80% was achieved in Minorities and Heuristic Learning. For Challenges further clarification was required between the codes Health and Home, School and Teachers. Removing the *Health* code and distributing those statements into a new code- *Distractions* was possible by defining mental health problems as distractions which interfered with and damaged the ability to learn.

Although there was some confusion between the Schools and Teachers codes it was agreed that these two codes would remain as they relate to two areas for which there is a body of education research. However changing the *Teacher* code to *Teaching* and renaming the *School* code as *Discouragement,* as it referred to barriers created by schools, helped in the coding process. With these slight modifications and careful attention during coding these two categories could be accurately differentiated. Making these adjustments brought agreement of scores for Challenges up from 68% to 77% and finally to 88%. Therefore the final level of agreement for each category was as shown here. This level of agreement confirmed the integrity of the method and a definitive set of codes were thus determined and presented in the results Chapter 8

Minorities	Challenges	Heuristics
83%	88%	95%

3.6 Validity and Reliability

Fundamental to this research is the validity of the tool used for data collection. This section describes the validation process of all Indicators statements and validation of the form of the questions and the questionnaire. It also explains the validation of the pilot study evaluators as relevant to the target population. Section 3.2.1 confirmed the validity of the Physics Competences Indicators by concurrent validation, and therefore they are not revisited here.

Blalock et al. (2008) advise strongly that all components of data collection are based on well-established research. Blalock investigated research studies of science attitudes in which he examined peer reviewed publications of the measurement tools used in studies published between 1935-2005. He found that a multitude of instruments have been used through the years that do not substantiate the associations made in their research conclusions.

Blalock also refers to the observation made by Noll (1935) that measurements should take a scientific perspective and work in a scientific method. Therefore this questionnaire was designed to only include established constructs and competences based on long standing research of leading educationalists, learning theorists and physics education researchers. Constructs and competences were based principally on the work of Eyre and her definitions of Advanced Cognitive Performance (ACP), cognitive processes and procedures of Bloom's Taxonomy and its updates by Anderson and Marzano (2006), and the Scientific Method, recently redefined in relation to secondary school teaching by Wenning (2006). In addition the variables of the Constructs and Competences were also concurrently validated as set out in Table 3-1 It is this concurrent validity which satisfies the criteria of good practice advised by Blalock.

3.6.1 Validation Process.

A validation process was staged throughout the research development. It required a number of panels of knowledgeable individuals who acted as jury to provide expert opinion and advice Table 3-12. A first line of evaluation occurred at each stage by the PhD supervisors, as leads in the Physics Education Research Group (PERG), and qualified in Physics, Chemistry and STEM Education. A second panel comprised of the extended members of PERG as physicists, teachers and researchers and undergraduate physics students from the University of Leeds, Department of Physics. A third group included an independent researcher from Leeds University with a background in Social Science and a physics education expert from the Department of Education. A forth group were physicists and one mathematician who were external to Leeds University and all had mid to long term careers outside academia and educational bodies. The fifth group were the staff and members of the physics research group of The Ogden Trust, an organisation that promotes and supports physics education.

Table 3-12: Validator Groups

Group Number	Composition	Purpose
1	Five physics academics from the Dept. of Physics and Astronomy and one chemistry academic, all working at Leeds University.	This group assessed the indicators for holding true relevance to doing physics and checked alignment with their view of physics education practice.
Group Number	Composition	Purpose
2	Three physicists chosen for their experience as university teachers/ researchers and three undergraduate physics students. Identified in the Results section as Academics and Students: Acad A/B/C and Stud A/B/C	This group reassessed the indicators for holding true relevance to doing physics in their experience from novice to expert.
3	Three education researchers, one with a background in Social Science and two with a degree in physics, but working as an educationalist and research statistician.	Evaluators of the method of investigation and its accessibility to the target audience based on their experience of education research.
4	Four Physicists and one Mathematician with mid to long term careers outside physics or in business/industry applications of physics. Identified in the Results section as Ex A/B/C/D/E, or as Graduates: Grad A/B/C/D/E	External physicists not working in academic physics education and representative of those who studied physics to lead to other careers
5	Seven Ogden Trust members i.e. Physicists with a specific interest in promoting physics education.	Independent physicists who had not been involved in earlier stages of assessment undertake an evaluation by way of pilot study.

The five stages of the validity checks are described as follows:

Stage 1: The Theoretical Concepts and Constructs and outline for the Questionnaire were checked by the Supervisors and members of PERG. Group 1 and senior members of Group 2

Stage 2: The Indicators were evaluated as true representations and descriptors of the Constructs and Competences by Groups 2,3 and 4 .

Stage 3 : Following the analysis of the evaluation in Stage 2 and using the evaluated Questionnaire outline from Stage 1, a first draft questionnaire was produced

Stage 4: A two part pilot study. Pilot Part 1 was conducted by Group 1 and Group 3 to check the overall content and style of the questionnaire. Of particular note was the assessment by the social scientist and physics educationalist on readability and participant interpretation of questions. They advised on question content which may be considered to be ‘leading’ and therefore could illicit a bias response from participants.

After redrafting the questionnaire, Pilot Part 2 was launched to a group of 12 members – made up of Group 1, undergraduate physics students, Group 3 and physicists from Group 5 as a target sample representing the target audience for the questionnaire, to assess its efficacy. Therefore the pilot study tested for two aspects of psychometric properties of the questions themselves, to ensure that the questionnaire was fit for purpose, as summarised by Creswell (2014a)

- That questions relate to the Constructs and Competences to be measured
- That phrases of the questions are clear and mean the same to all participants

In addition this working group checked for

- Ease of use
- A measure of interest, usefulness, reward for the participant, to help optimise response levels

Analysis of the responses to the draft questionnaire checked:

- the validity and reliability of questions among a more diverse group than Group 1 and 2
- the validity of responses and their levels of differentiation and discrimination. This was an assessment of content validity. Ary, Jacobs and Razavieh (2002) defined content validity as "*the degree to which the items on an instrument representatively sample the underlying content domain*". In other words: The extent to which an operationalization adequately represents all aspects of the theoretically grounded phenomena (in this case the constructs and competences) that are to be measured; do the indicators represent the meaning of the Constructs and Competences and therefore do they yield meaningful data when analysed.

Stage 5: External Review**:** Two final validity checks were carried out by two members of Group 3: an expert in Physics Education Research and a physicist and specialist in quantitative analysis. They examined a summary report on the Literature Review, the questionnaire and its pilot study analysis. Their feedback finalised all previous validity assessments but also advised that; the scope of the research should be narrowed and defined to a sharper degree and that further work on how the data should be analysed should be carried out before the questionnaire launch. Addressing these points the Research Questions were revised and two elements of the original scope were removed. As a result of the pilot study data analysis, further question 'cleaning' was applied.

In addition, through these cycles the questions were shortened and clarified and the number of indicators used and the number of questions was reduced. The proportion of open style narrative questions were reduced and replaced by multiple-answer, selection style questions. In this way the instrument was made faithful to the revised Research Questions, greater clarity was achieved for ease of understanding the questions and the time for completion reduced from 90 minutes to ~20 minutes.

3.6.1.1 Validity of Construct and Learning Competences Indicators

In Stage 2 the validity of the Indicators as measures of the construct validity were investigated. To do this, raters were employed from Group 2,3 and 4 to assess how well the indicators reflected and were robust measures of the constructs, competences and their variables. To ensure a faithful assessment, raters were provided with the definitions of each of the variables (Section 1.2.2 and Section 2.1.1) and notes on the purpose of the study, the setting, and the target population. The inventory of indicators to evaluate were preceded by a personal email to each rater advising them on their role as evaluators. The raters could then proceed to rate each indicator as representative of the construct or not. The percentage frequency response from the group of raters, for each indicator have been included in Table 3-2, Table 3-3, Table 3-4, Table 3-5, Table 3-6, Table 3-7, to avoid duplication of long tables.

It was found that all indicators received a minimum of 30% selection scores. When considering that this low score might be interpreted to show these indicators to be of low validity, it was found on inspection that invariably the indicators were those that represented the highest cognitive performance competences, recognised by the academics and those still working with physics and therefore it was important to keep these indicators as important differentiators.

3.6.1.2 Validity of Physics Competence Indicators

Although the Physics Competence had been concurrently validated, (Section 2.2.3). it was necessary to check on the content validity (Ary, Jacobs and Razavieh 2002). The validation was the iterative process as described in the section 3.6.1.1.

The results are summarised in Figure 3-1, Figure 3-2, Figure 3-3, Figure3-4 , Figure 3-5 where each figure represents one of the five competences. For each competence, its Indicators are shown on the horizontal axis in order of increasing agreement (increasing average values). The vertical axis is the average percentage agreement of raters who chose each indicator as a valid and true representation of the competence, with overall score range 24 - 100%. Rating are the average for 3 subgroups which made up the rater in Groups 2 and 4. Sub group *Students* comprises three 3rd year physics undergraduates. *Graduates* comprise four Physicists and one Mathematician with mid to long term careers outside physics or in business/industry applications of physics. Whilst sub group *Academics* were three, mid-career physics academics who have a post graduate qualification and similar length of career as the Graduate subgroup. The combined groups had a female to male ratio of 7:5. Although this is not the representative ratio of female to males in physics it does reflect that females were more willing to take part in this assessment work. It was taken as given that gender did not have any influence on assessment.

As was the case with the other competence indicators, higher percentage scores may be considered to be a measure of the strength of the indicator as a true representation of the competence and indicators with lower scores less useful. However aptitude, experience and the physics knowledge level of the rater may have influenced the choice of indicators. This was deduced when Students were seen to pick fewer indicators than experienced, working Graduates and Academic physicists as shown in each graph. In particular, Students less frequently chose indicators in Thinking + Reasoning and Modelling which on inspection were shown to represent the higher cognitive performance. It could be concluded that the Graduates and Academics as expert raters recognised the value or fully understood these particular indicator statements. Therefore inclusion of all indicators provides a means of measuring and differentiating levels of competence in respondents at a broad range of levels of knowledge and experience. It might be expected that the academics would yield 100% responses for all indicators but this is not the case for T6,T7 and P9 and therefore these indicators may, in some raters view, be better placed under another competence. This is considered again in Section 5.4.

Note also that this validation process uses very small number of raters and therefore small changes are reflected by large percentages.

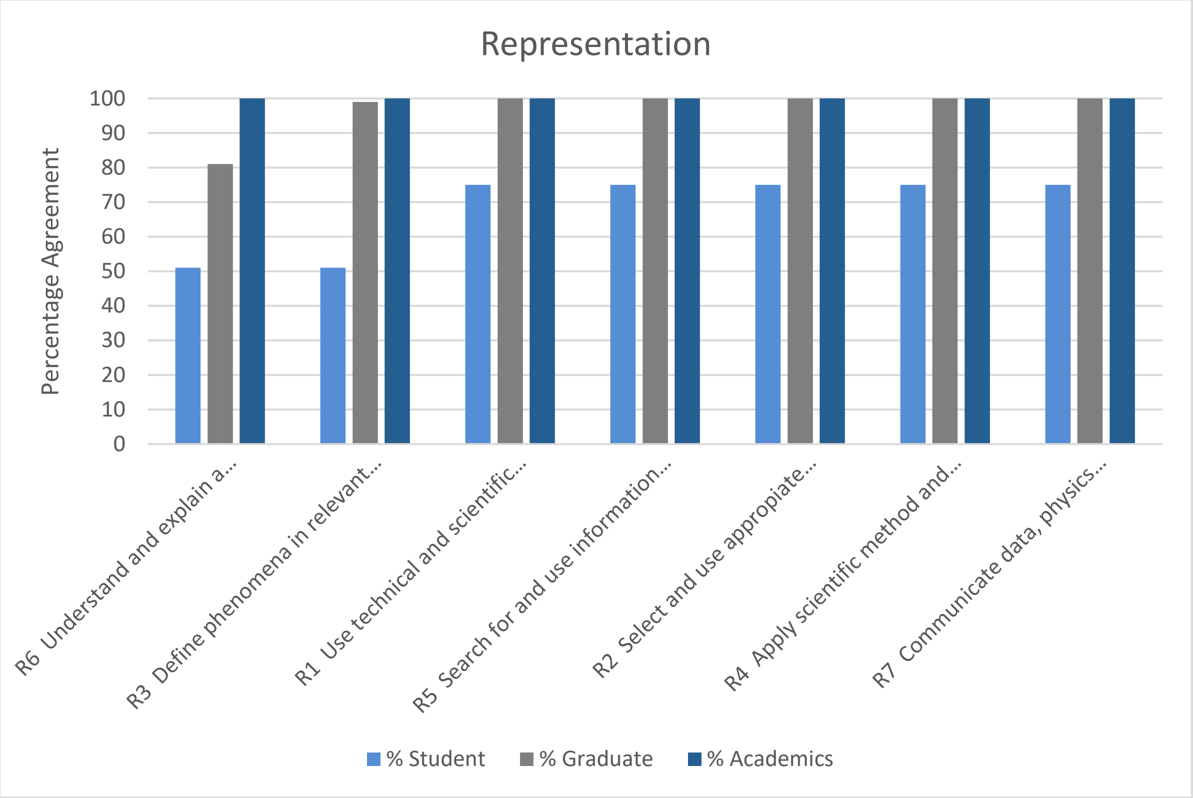

Figure 3-1: Validation – Representation Competence Indicators.

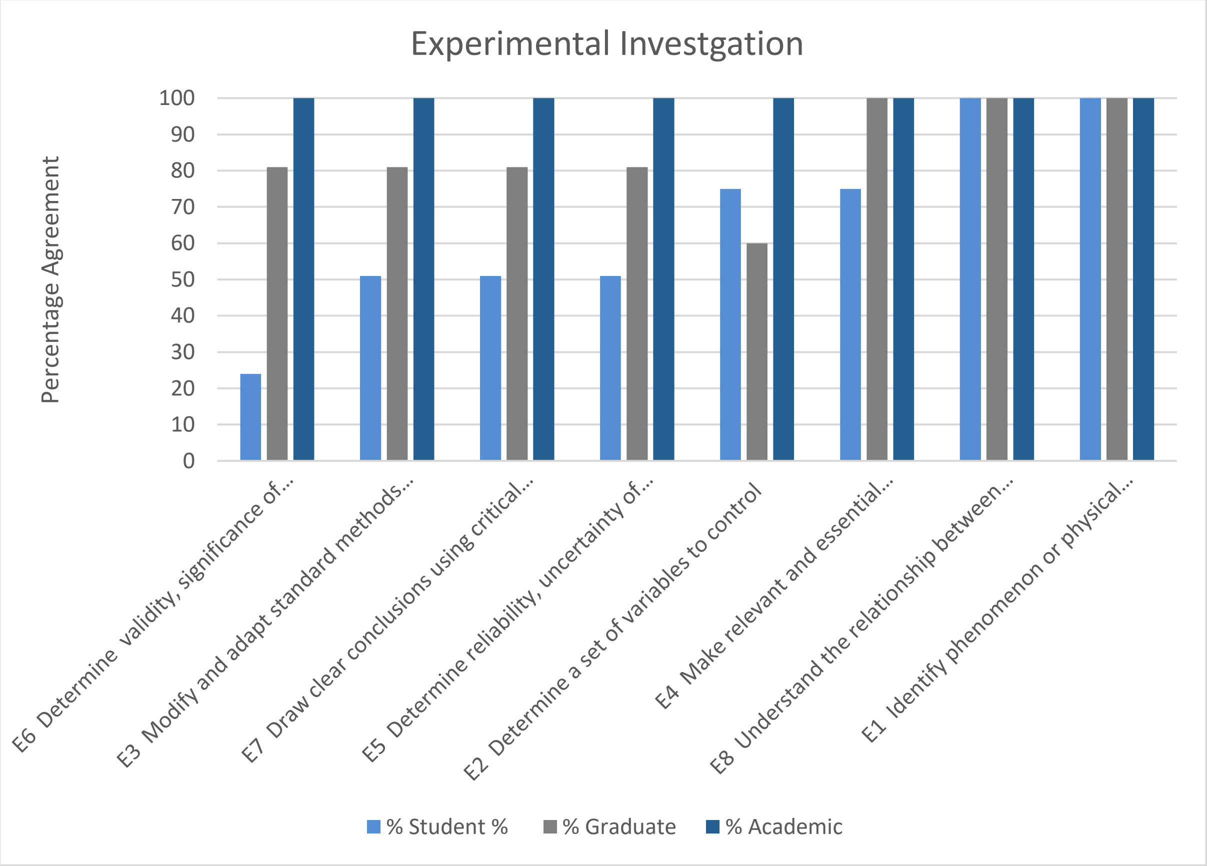

Figure 3-2: Validation – Experimental Investigation Competence Indicators

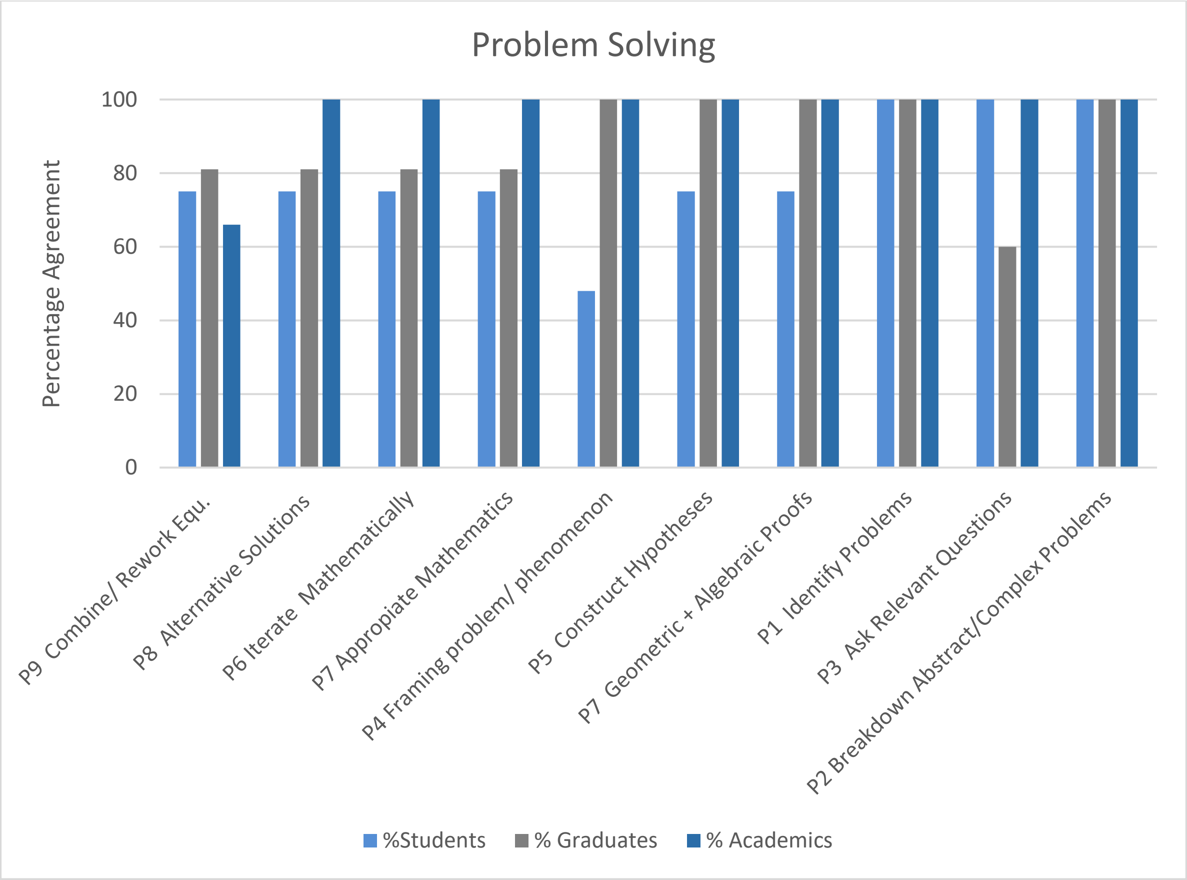

Figure 3-3: Validation – Problem Solving Competence Indicators

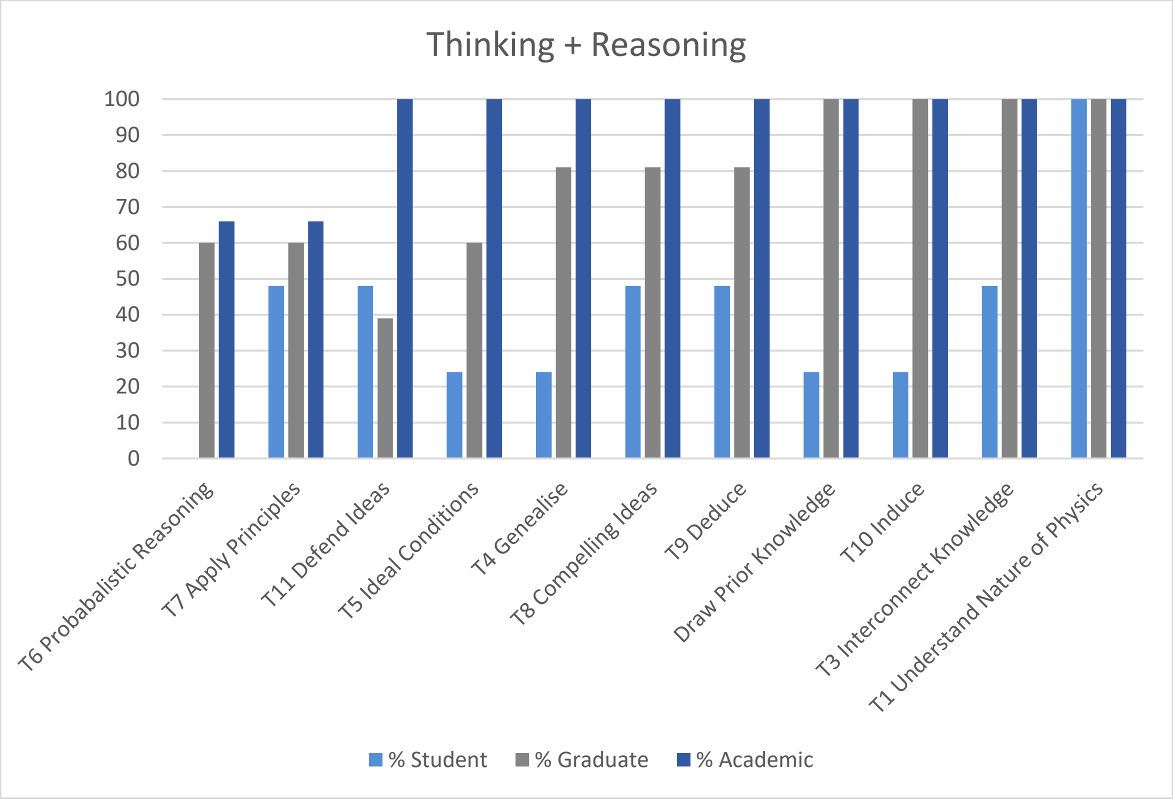

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Figure3-4: Validation – Thinking and Reasoning Competence Indicators

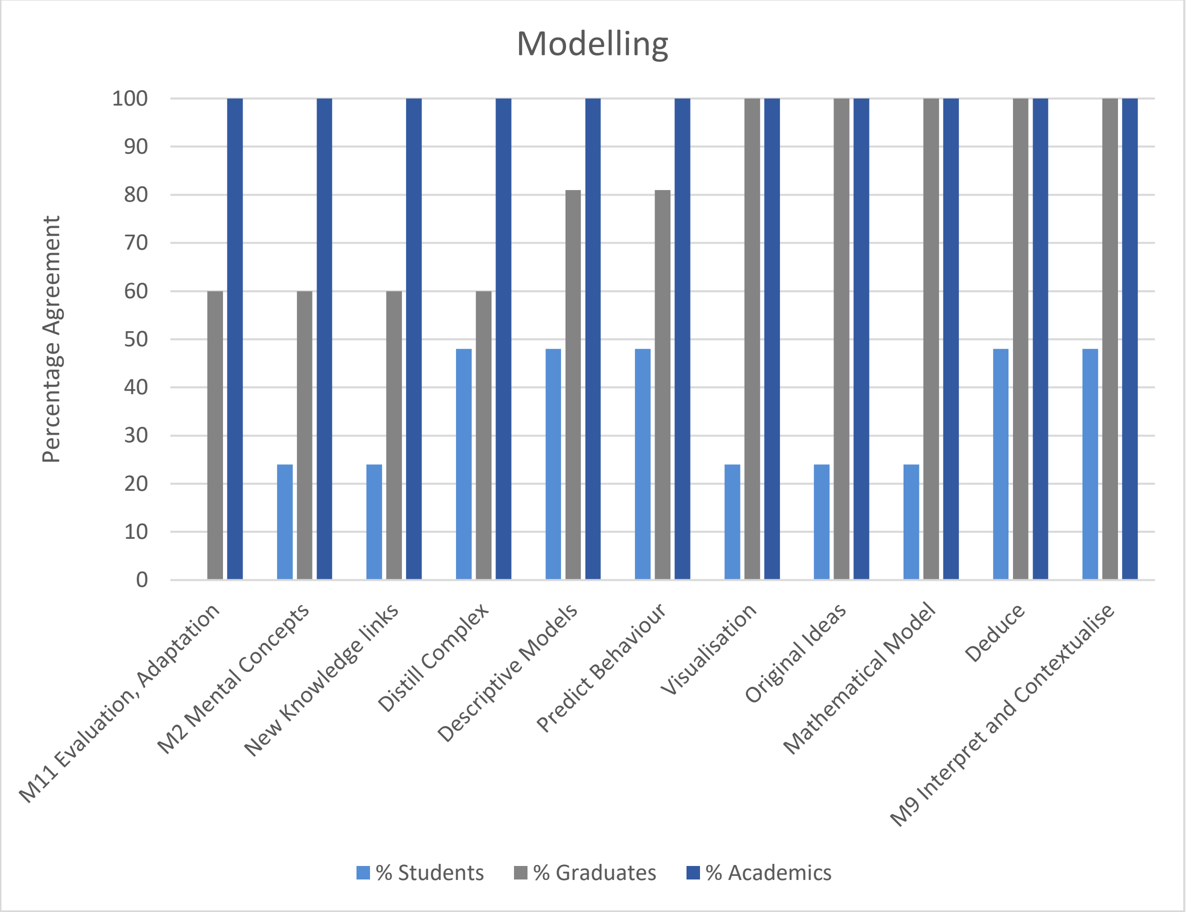

Figure 3-5: Validation – Modelling Competence Indicators

3.6.1.3 Validity of the Scale of Mastery

The validated indicators were used to assess the designed four point scale as a means of measuring the mastery of physics competence. Members of Groups 2, and 5 were asked to report their perceived level of mastery of each indicator using the designed scale ranging from mastered with Ease to Challenging. Figure 3-6 shows the results for the Problem Solving Competence as a representative example, with Indicators ranked in order of decreasing levels of Ease. This confirms that the scale effectively differentiated levels of mastery.

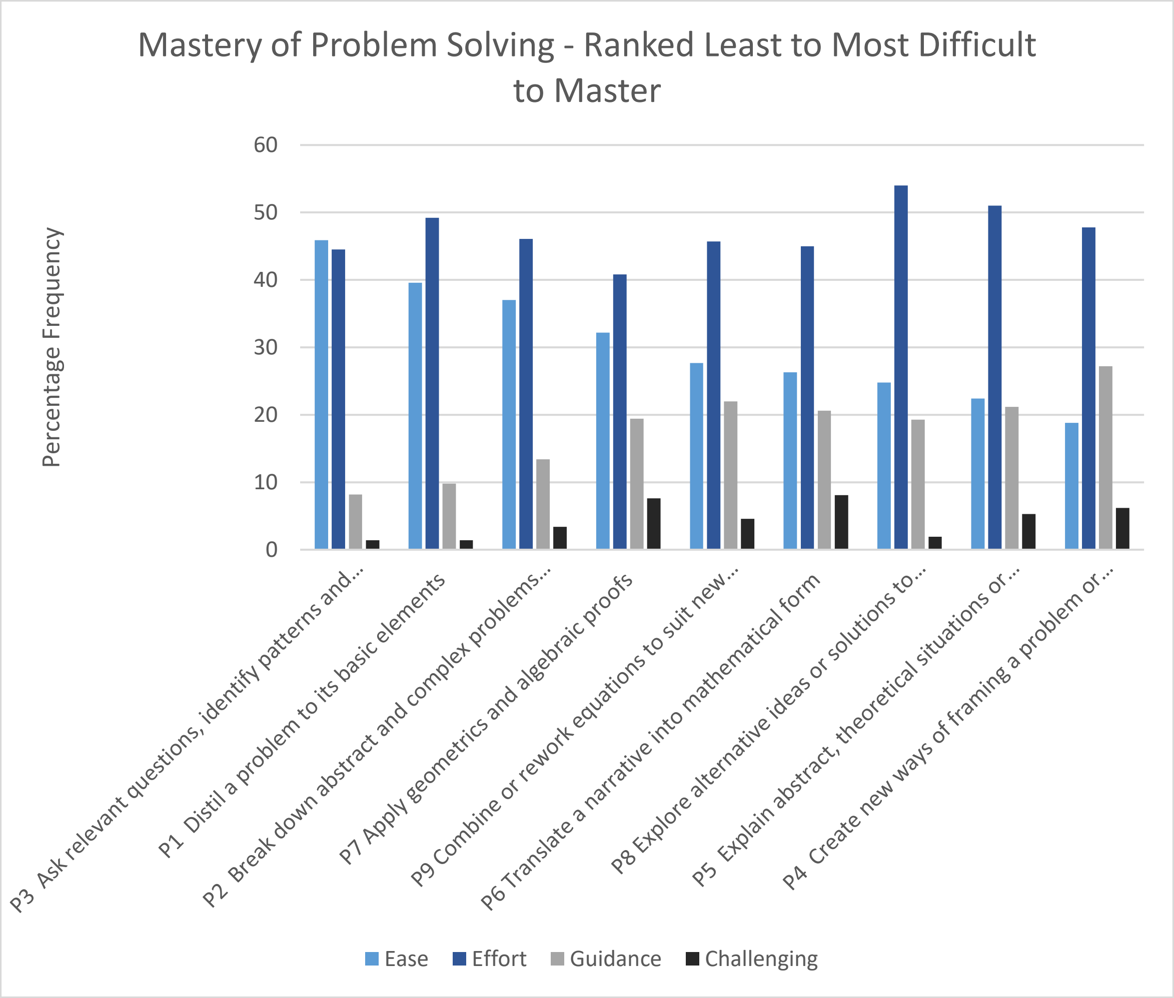

Figure 3-6: Scale of Mastery – Indicators ranked in decreasing order of Ease

3.6.1.4 Reliability and Diversity of Population Responses

A pilot study was completed to check if the questions would discriminate the diversity of the population and to measure inter-rater reliability on evaluating the indicators. The pilot study comprised Groups 1,3 and 5. Since the target group for data collection was aged 18-75years+ therefore this pilot group was representative of the target population in age and expected career range. The gender ratio was 8:7 female to male for the pilot compared to 1:5 in the current population of physics students and the respondent population was 1:1. Figure 3-7 shows the cumulative percentage scores for each rater for all 8 Constructs and Competences, hence the vertical axis scale ranges from 0-800%.

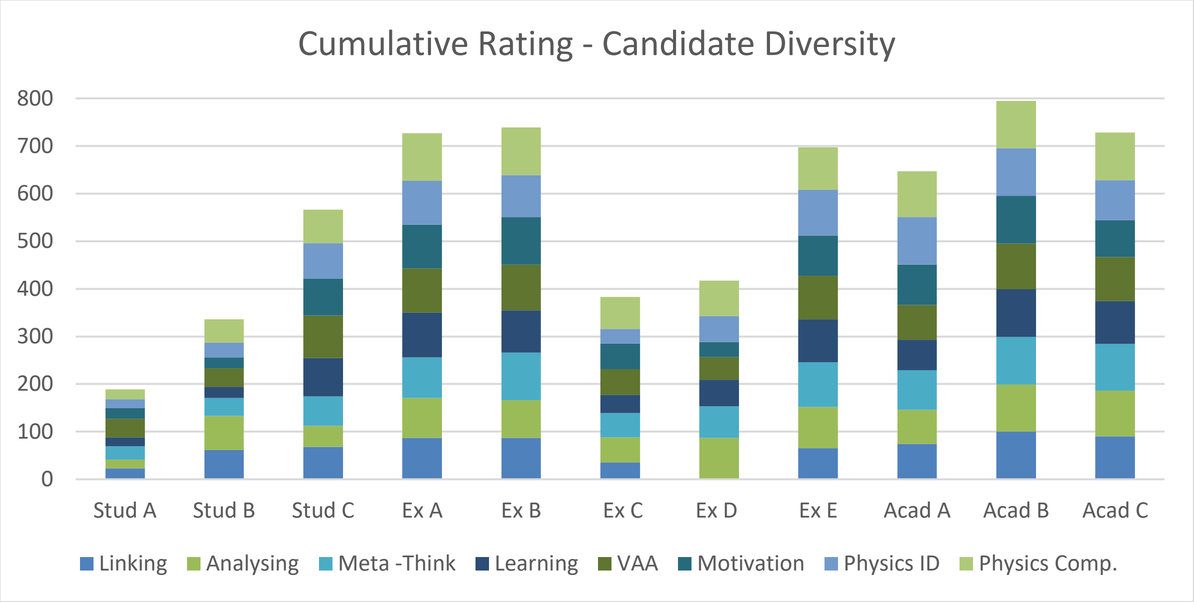

Figure 3-7: Inter-rator Study

The results show the level of consistency among the raters for their scoring of all Construct and Competences. Variation in the levels of total score per rater, Students 208 - 582% , Externals (as Graduates) 385 - 731% and Academics 650 – 800% demonstrates the importance of the wide range of indicator statements in the questions, as it shows that this range is necessary to capture the diversity of learning and experience of those who study and work in physics. It also confirmed at the development stage that use of the indicators must be calibrated for use with different target groups, or recorded in context, and therefore this finding also supported the development of the mastery scale . This finding is consistent with the results for the five Physics Competences as a set as shown in Figure 3-8 and Figure 3-9.

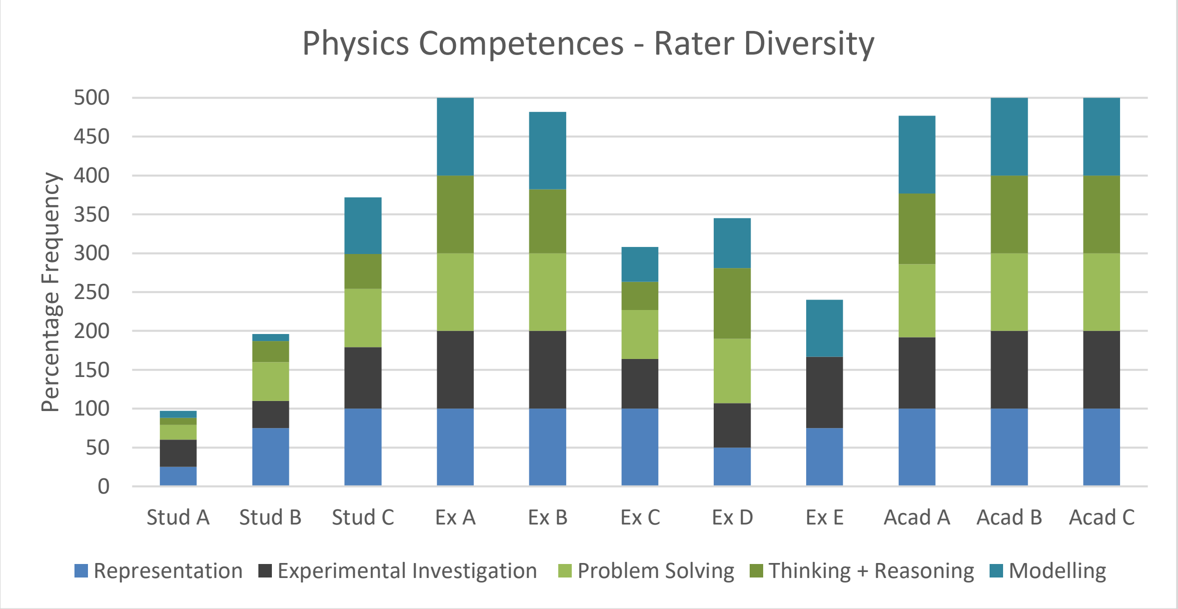

Figure 3-8: Rater Reliability and Comparison between Students, Graduates and Academics

Examining the response for the raters grouped as Students, Graduates and Academics Table 3-9, shows percentage frequency score ranges: Students 33- 69%, Graduates 79- 97% and Academics 94-100%. Although from a small test sample these results are as might be expected. Students and Graduates, are responding, most likely, with a narrower level of doing-physics experience and lower bank of physics knowledge. Research by Snyder (2000) and Priest and Lindsay (1992) discusses this Novice to Expert difference and assigns it to the progression from a purely model based problem solving and understanding level to one which connects models to coherent theories. This would explain why students recognised fewer of the indicators per competence, as well as acknowledging that the teaching of physics is hierarchical, therefore validating that the questionnaire measures meaningful data.

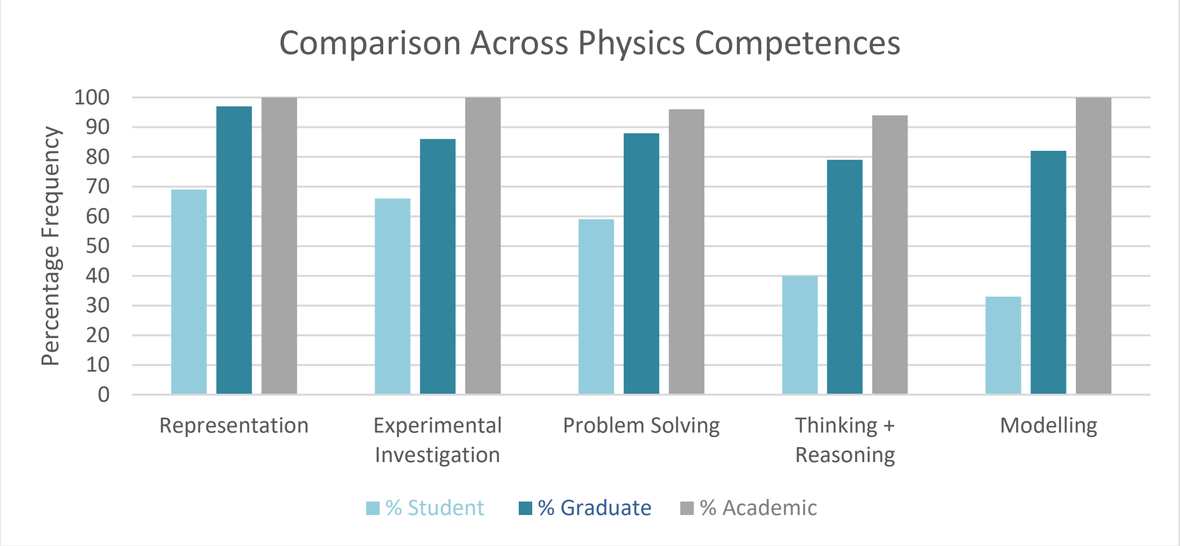

Figure 3-9: Rater Reliability and Comparison between Students, Graduates and Academics

3.6.2 Reliability Statistics

SPSS was used to perform a rater and inter-rater reliability analysis with Cronbach Alpha and Kappa statistics. (Bell and Opie 2002)

Cronbach Alpha statistic was performed as a measure of internal consistency and values should range 0 to 1 and a value of 0.7 and above is the desired result.

Kappa statistic was performed to determine the consistency among raters and typical results are:

0.0-0.2	Slight agreement
0.21 – 0.4	Fair
0.41 -0.6	Moderate
0.61 – 0.8	Substantial

The analysis was carried out using the groups of Students, Graduates and Academics as the raters and the data analysed for consistency were: the Analysing and Creating set of Indicators and the Physics Competences Indicators. The Creating and Realising set was chosen as representative of all other indicator sets as it was the largest raw dataset with a total of 76 indicators. The 46 Physics Competences Indicators were tested at the Ease level response. Results are shown in Table 3-13 and Table 3-14.

Table 3-13: Cronbach Alpha and Kappa Coeficients of Consistency and Reliability at (p<0.001) Creating and Analysing Indicators

Analysing+ Creating	Alpha	Alpha Accepted Level > 0.7	Kappa	Kappa Agreement Level
Students	0.074		0.077	Slight
Graduate	0.652		0.267	Fair
Academics	0.751	> 0.7	0.435	Moderate

Table 3-14: Cronbach Alpha and Kappa coeficients of Consistency and Reliability at (p<0.001) Physics Competences Indicators

Physics Competences	Alpha	Alpha Accepted Level > 0.7	Kappa	Kappa Agreement Level
Students	0.89	>0.7	0.194	Slight
Graduate	0.99	> 0.7	0.614	Substantial
Academics	1.00	> 0.7	0.935	Perfect

Cronbach Alpha results show high levels of consistency for the analysis of the Physics Competence Indicators for all three groups. The student response for Analysing and Creating is less than accepted values and this outcome may be understood by comparing the variation of response rates for the two competences, for each student as shown in Table 3-15 below.

Table 3-15: Response Rates for Students

	Student A	Student B	Student C	Average
Analysing + Creating n=76	16%	47%	67%	43%
Physics Competences n=46	35%	35%	79%	49%

These results are consistent with the descriptive analysis, which showed that the three students varied considerably in their scoring and therefore the average covariance would be low. This may be a measure of the diversity of Student response that needed to be accommodated or that they recognised the physics competences but did not have a full understanding of the processes of physics.

Kappa results were slight to moderate reliability for the Analysing and Creating Indicators. In the case of Physics Competences, Academics scored optimum reliability while the Graduate group were more consistent than the Students and this could be an indication that the responses show discrimination between the three groups for these indicators.

Interpreting these results suggests that the Cronbach Alpha figures for Academics show that we have a comprehensive set of indicators which give consistent results and therefore a high coefficient of reliability of measures of these competences.   The lower figures for Graduates and Students confirms the recognised hierarchy of physics knowledge and competences. Therefore It could be concluded that this spread of results encompassed the academic range, novice to expert. The range of Cronbach Alpha and Kappa coefficients shows that the three rater groups are distinct and therefore the Indicators enable the capture of the diversity of respondents' learning and working with physics.

3.7 Summary – Validity and Reliability

The validation process of all Indicators statements and validation of the form of the questions and the questionnaire were set out. Five panels of knowledgeable individuals who acted as jury to provide expert opinion and advice were used for the validation process. As five different groups, or in combination, they were required to assess and evaluate different facet in the validity and reliability process. Importantly for a pilot study the evaluators were representative of the target respondents by age and career range.

The aspects evaluated: were questions accessible to the readership, was the interpretation of Indicators and questions consistent among respondents, were responses capable of yielding significant metrics with sufficient discrimination of the target population and providing a focused and satisfying experience for respondents.

Statistical analysis using SPSS calculated the Cronbach Alpha coefficient for consistency of interpretation of indicators by raters groups.   Kappa coefficients of reliability at the 95% confidence level showed good measures of agreement between Academic raters for Physics Competences and discrimination between rater groups and therefore it was shown that an efficient data collection tool had been produced for measuring Physics Competences and discrimination between Students, Graduates and Academics for learning and performance in physics . While the insufficient values for consistency among the Student group for Analysing and Creating results would indicate the diversity of the student group.

3.8 Questionnaire Design

This section explains the format and structure of the questionnaire, layout of questions, their style and content, the target audience and methods of access to this audience.

The target outcomes were to gather data, both quantitatively and qualitatively, to capture the 'whole' of physics learning and the physics learner in the most effective way for a single data collection approach.

3.8.1 Questions

The initial questions were scoped on the constructs, competences and Indicators as identified in Section 3.1 and Physics Competences in Section 3.2.

Creation of questions was by the author and checked in internal review among the Physics Education Research Group academics at Leeds University to guarantee detection of a faithful alignment with the Research Questions and the theoretical concepts. Reducing the time to complete the questionnaire was a constraint and sharpening the focus of the research meant that, where necessary, appropriate changes were made and a further check in the form of a matrix was used to map the Research Questions against the questionnaire entries. In this way a number of the indicators, as sub components of questions were removed or merged with other indicators. The final indicator selection and rationale for each question is set out below

3.8.2 Questionnaire

A copy of the online questionnaire is set out in Appendix B,

Structure of the Questionnaire

Page 1 – Background Information and Consent Form

Page 2 – Demographics + Record of participants Learning History and Career

Page 3 – Building the Learning Profile

Page 4 – Doing and Mastering Physics

Page 5 – What Else Does it Take to Succeed in Physics

Page 6 – Additional Information Respondents may wish to Provide

The questionnaire consisted of 22 questions with sub-sections.

Page 1 introduced the respondents to the aims of the research by a brief outline and provided a set of guide notes about completing the questionnaire, it explained how data would be analysed and stored and how the outcomes would be made available.

Question 1 requested consent for use of data.

Question 2 required respondents to enter a code by which they would be anonymous but traceable if they requested their data retracted. The code was the first three letters of their name, the month they were born and town or city of their secondary school. This school location information provided a means to monitor the geographical spread of schools attended throughout the UK and not the current respondent location during data collection.

Question 3-11 were questions to draw in the demographical information.

For Question 12 onwards respondents were asked to answer questions by reflecting on their physics- student- self at secondary school level and with reference to their A Level physics knowledge, learning experience and experiences of learning.

Question12 was a catch-all question to gather data on physics identity, learning characteristics and learning competences as well as markers on ability. Its purpose was threefold:

- First, to produce an uncomplicated sketch, the Learning Profile, of a population who had succeeded in doing physics.
- Secondly to gather this overview before the more intense Physics Competence questions, that required much more of the respondents.
- Q12 aimed to capture the interest of the respondent and encourage their perseverance for completion of the questionnaire.

Data was gathered by dichotomous responses to a list of 69 indicator statements, such that respondents could choose any number of indicators which described their former student self.

Q13-17 covered the five Physics Competences which were described with 46 Indicators. These required respondents to reply to each indicator using a scale of mastery that reported that they could achieve doing the indicator; with Ease, or with typical amounts of Effort, or that they would have required Guidance or that they would have found the task Challenging.

Questions 18-22 were sub divided according to the constructs of Learning Character and Physics Identity, and explored why the respondents had chosen to study physics for A Level as well as 5 sub-sections invited personal narratives. More details are provided in section 3.8.3

In total the use of indicators made up 303 dichotomous items and 46 scale responses.

In designing the questions, how the data was to be analysed was considered as shown in Table 3-16.

Table 3-16: Questions and Competence Analysis Matrix

Question	Question Focus	Construct /Competence
1	Consent	
	Respondent Demographic Context	
2	Code, Secondary School location, Country	Demographics
3, 4, 5	Demographics: Age, Gender, Ethnicity,	Demographics
6, 7. 8	Education: School Type, Exams and Grades	Demographics
9, 10	Education: Tertiary, Qualifications, subject focus	Demographics
Question	Question Focus	Construct /Competence
11	Career Path, Physics Knowledge + Grounding	Demographics/ Physics+ Learning Competences
	Learning Profiles of Physicists	
12	Physics Learning Profile	All Constructs
	Physics Competences - Mastery	
13-17	Physics Competences – Doing and Mastering Physics	Physics Competences
	Challenges, Motivation, Self-System	
18	Learning Character + Competences	Learning Character+ Competences /Values Attitudes, Attributes
19	Learning Character-Physics Classes	Learning Character/Physics Identity
19a	Impact of Minority Status	Challenges and Positive Impact
20	Physics Identity	Physics Identity
Question	Question Focus	Construct /Competence
21	Influences on Choosing A Level Physics	System + Personal Challenges/ Internal + External Motivation
21a	Challenges While Studying Physics	Physics Identity/ system Challenges/ Internal + External Motivation
21b	Positive Childhood Experiences and Informal Learning	Learning Competences + Physics Competences
22	Any Other Information to Contribute	Any of the Above

3.8.3 Narrative Questions

Creswell and Davies (2007) recommend the use of a Mixed Methods approach to capture both qualitative and quantitative data, hence the collection of the personal narratives of respondents through five open-ended questions which allowed the respondents to give any information they consider may be pertinent to the study. This approach allowed for unique responses to be captured and possible analysis in a phenomenographic study.

3.8.4 Linguistics

It should be noted that the questions were expected to be linguistically UK centric and therefore to match the needs of the main target population. Although the questionnaire frame did include participants who were outside the UK, it was assumed that their choice to take the questionnaire signifies their linguistic equivalence.

3.9 Participant Criteria

For this situation of learning physics a relevant internal condition is Intelligence, where intelligence is defined as a measure of the general ability to learn. Taking into consideration this ability to learn physics was addressed by targeting a population who had achieved a national qualification in physics at senior school level - the A level award or its equivalent. Therefore this condition was satisfied and would act as a lens in the investigation and evaluation.

It was accepted that at this level respondents could provide good quality responses because they have:

1. Understanding of the Nature of Physics
2. Ability – They were successful in their study of physics
3. Prior Knowledge – participants who can draw to mind physics in order to relate to the physics specific questions and have a sufficient level of physics knowledge and experience of doing physics to give informed and useful responses.

Therefore the target population provided feedback on learning and understanding of physics. Their responses are both physics informed and physics related.

3.9.1 Participant Protection, Experience and Satisfaction

Participants in research must be afforded protection and so Research Ethics clearance was achieved. In addition they must have a good experience in the provision of data and feel satisfied that it was a worthwhile experience, Creswell (2014a). These latter two features are explained in more detail below.

In addition these features contribute to the validity of the data collected. This validity results from the anonymity of the respondents, as pointed out by Ary et a.(2002) "*It is reasonable to assume that greater truthfulness will be obtained if the respondents can remain anonymous*".

The sampling frame used, targeted the population in an independent fashion, via gatekeepers or through the online social media platforms, therefore ruling out any bias such as the Halo Effect, or influence of the researcher's views upon the respondents. Limitations of the sampling frame are set out in Table 2-8. A further level of content validity may also be afforded by the nature of any online questionnaire. This provides a confidential space for the participant and also allows them a choice to respond when they have gathered their recollections of their physics learning. There was the option to save their replies and return when their answers and ideas had time to be appraised and consolidated with reflection.

The following features were incorporated.

- Complete anonymity guaranteed and how this is achieved made clear to participants at the outset.
- Consent for use of data and all potential respondents were informed that the data was being used for a dissertation and how the data would be disseminated.
- A relevant, clear and interesting title " Success in Physics" such that the target group would consider the questionnaire a valuable and useful occupation of their time and effort.
- An informative introduction that would maintain and further enhance interest and draw on the respondent's time as well as the record of ethics clearance.
- Instructions on how to complete the questionnaire and any future request for feedback were explained.
- Questions were styled to be clear, purposeful and progressive. Questions were a close fit to the Research Questions and followed coherent themes.
- The number of questions were reduced to a minimum necessary to obtain the required data.(Ary, Jacobs and Razavieh 2002), in the minimum of the respondent's time.
- Sufficient intellectual experience for participants without being taxing
- Broad spectrum appeal to emergent, developed and experienced physicists and physics learners

- Interesting presentation of questions to provide the opportunity for respondents to feel satisfied on completion; i.e. that they had shared useful information that has a high chance of making a relevant contribution to the research.

In addition the design also had these features of optimum research use.

- Ease of circulation
- Ease of data download
- Data collection optimised for streamlined analysis

3.9.2 Demographics

Recording demographics was a means of monitoring the data collection and setting controls and variables, dependent and independent, which could be manipulated for data analysis. The following features were recorded and the rationale for using each demographic measure is set out.

3.9.2.1 Age and School Exam Qualification

During the education period for the age range 18yrs to beyond 75 years covered a number of significant changes in the education system, curriculum and assessment procedures and criteria. By recording age spread within bands, allows for examination of correlation with these education changes. In this respect Age could be used as a lens for part of the analysis. Those respondents aged over 45 years made up the cohort who had studied the O level, CSE qualifications and corresponding A Level. However it was found that one respondent had returned to education later in life. Data from those respondents younger than 45yrs form the new GCSE cohort and a number of more recent curriculum and examination changes within that. It is important to compare and contrast these two groups because of these distinct differences of the examination systems.

3.9.2.2 Age Range: Career and Expertise Perspective

The age ranges included in the data collection were**:** 18-22yrs, 23-27yrs, 28-35yrs, 36-45yrs, 46-55yrs, 56-65yrs, 66-75yrs, 76+ yrs. The age ranges were not in equal proportions but were chosen taking into consideration the stages of qualification and employment. Therefore the five year span from 18-22 would encompass the majority of undergraduates. Similarily the five year span, 23-27yrs captured those in PhD research or first years of employment. An eight year span, 28-35yrs covered the early career growth stage. A ten year span, 36-45yrs covered the established mid career phase. 46-55yrs takes into account the senior employment phase and also demarcates the youngest cohort among those who would have studied with the old system of O Level and A levels examinations.

Wheras the ten year span, 56-65 yrs captures the most senior part of the workforce and their inclusion along with the retired cohort 66yrs+ increases the number of respondents from this older O Level examination system era Also note that the overall range gave a 27 year age range from 18yrs – 45yrs and a 29 year age range from 46-75yrs old, i.e. 27 years of the new GCSE era compared to 29 years of the older O Level era.

As a reflective study, depending on the age of the respondents, younger versus older, the lens of reflection will differ. Van Heuvelen (1991) has shown that the differences in the conceptual knowledge bank between the novice and expert physicist must be taken into account when considering formation of new conceptual understanding. This study limited itself in scope and so although the data exists, analysis was not performed with this age difference as a lens.

3.9.2.3 Location

Both regional and national locations were recorded; based on the decision to make data collection UK centric so that findings could be offered in relation to education policy and practice throughout the UK. Respondents indicated which part of the UK they were educated in for secondary school level, to correspond to regional variations in provision. Since the A Level system was dominant, then this is the reference used throughout analysis and other UK qualifications are equated to the A. Level using an equivalence conversion table. Due to the online methods of circulation of the questionnaire and the multiple nationalities of the UK the questionnaire also collected records of those educated outside the UK as an alternative grouping.

Recording the nearest main town to the secondary school in which the respondent was educated allowed checks on a regional basis and helped avoid skews such as London centric responses due to higher employment in London or other high employment areas. Geographical spread was monitored at intervals throughout data collection.

3.9.2.4 Education and Careers

Participants were asked if they had other qualifications in physics beyond A level. Also those who did not continue with physics beyond A level were asked what other study, if any, they followed. This meant that data could be compared for graduates and non-graduates, STEM vs non-STEM, physics graduates compared to non-physicists and physicists at different levels of academic experience; that is Diploma, Degree, Masters levels and Doctorate could be compared and contrasted. In this way responses could be analysed against levels of physics learning.

3.10 Launch and Supervision.

A review of the literature on instrument design (Dillman 2000; Ary, Jacobs and Razavieh 2002) revealed the major concern of data collection by questionnaire would be low percentage return (typically 4-16%).

However using social media and STEM membership organisations enabled access to large groups of physics trained people through many data collection sites and so a large response was achieved by staged sampling**.** Another advantage of this sampling frame was that returns were completed by those who felt the topic was important to address and they had sufficient interest for a committed and diligent response, without bias related to affiliation to Leeds University or the lead researcher. Disadvantages became apparent during data analysis when it was noted that the respondents were predominantly graduates and STEM educated, 98% and high achievers at secondary school level.

The population included the following Strata**:**

- Male: female, Respondents could also state a non-binary gender or if they preferred not to say.
- Age ranges - Novice vs Expert Physicists
- Physics careers vs Non Physics careers
- State School Educated , Independent Sector , non UK education

Or clusters of any of the above e.g. Female, Specific age range, Expert physicists

Population biases exist in physics (i.e. fewer females, fewer from certain ethnic groups), as discussed in Chapter 1 and evident in the national statistical education data. The programme of data collection had two possible options to cope with these biases.

Data collection used Staged Sampling and invited responses in stages until sufficient data was collected to represent each stratum correctly. This was achieved by monitoring from Question 2.

3.10.1 Circulation

The following organisations were key allies and stakeholders who supported the research by sharing access to their networks of members who would be eligible for the questionnaire. Each set of members, by belonging to these bodies, have already indicated their interest in supporting education. This fact had been taken into consideration to improve the response level to the questionnaire. Although this approach made the target audience a self-selecting group who may be biased towards education, this was considered to be a positive attribute in that the responses are likely to be given adequate study and thought and therefore the best quality return. The key stakeholders are detailed Table 3-17.

Each of these organisations were approached through a gatekeeper contact known to the author and the PERG academics. Similarly students and staff of Leeds University, Queens University, Belfast, Aberdeen University and Cambridge University were also asked to circulate invitations through their staff and students using the introductory emails and letters provided. These emails and letters had been evaluated, trialled and enhanced at the evaluation stage.

Conveying the correct messages would be important at the gateway to the sampling frame and therefore needed to inform and secure interest to enable uptake.

In addition to the circulation of the questionnaire through these organisations, social media platforms were also used. Hence the circulation was extended by the use of LinkedIn and a dedicated Twitter account @Doing_Physics was set up. Many physics related networks have twitter accounts. Examples are @ChatPhysics, @WISE, @STEMettes, @PhysicsWorld, @Code.org, @STEMWomenUK, @WomanthologyUK, @IOPteaching, etc. Further circulation was achieved by using hashtags such as #physics #STEM #doingphysics #Engineering.

Table 3-17: Distribution of Questionnaire Gateways

The Ogden Trust	The Ogden Trust is the sponsor for this PhD research. The trust aims to increase the uptake of Physics for all at post 16, particularly underrepresented groups. The Trust works with a network of schools and 28 universities. The Questionnaire was circulated to its outreach officers.
STEM Learning Ltd	Works to achieve a world-leading education for all young people in Science, Technology, Engineering and Mathematics (STEM) through partnership with STEM based industry and managing STEM Ambassadors throughout the UK; who work with school pupils in extracurricular formal and informal learning. There are almost 40,000 STEM Ambassadors and a large portion of these are Engineers who will have studied Physics up to A level
Engineering UK/ RAE / IMechE/IET	The Engineering community have a long history of campaigning for more young people to be educated towards Engineering. This means that physics is a key subject for them. There are 120 Engineering bodies such as IMechE, ICE and IET which have networks of engineers involved with schools.
Institute of Physics IOP	The IOP provides an active and authoritative voice for physics. Working in all areas that affect physics, from schools education through to research and innovation. The IOP supplies timely, evidence-based, scientific advice and in-depth analyses to governments and other agencies. The IOP provides physics education resources and teacher CPD. IOP has a national network of members
Daphne Jackson Trust	Daphne Jackson was the UK’s first female professor of physics and lifelong campaigner for encouraging women to return to their careers in science and engineering. The trust enables women and men to return to research with confidence after a career break.
Royal Society of Chemistry	The Royal Society of Chemistry has a large membership and plays an active role in promoting education. It performs a similar function to the IOP.

3.11 Summary - Questionnaire

The data collection targeted groups of adults who have at least one nationally recognised qualification in physics at school level e.g. A level or its equivalent. As an entry point to the questionnaire this ensured that the participants had essential core physics knowledge and so could provide reliable and relevant feedback on learning and understanding of physics.

The questions in the range Q12-22 were designed to require respondents to select from lists of Indicator statements with the option of dichotomous responses. Questions 13-17 were scaled questions relating to the Physics Competences such that respondents could report on their mastery of the specific physics competences on a four point scale. Narrative questions were included to allow respondents to provide their personal learning journey and the influences and factors enabling success in physics. The questionnaire was launched online and by email through STEM stakeholders and STEM related social media platforms.

The questionnaire was launched on 22nd March 2019 and closed on 30th September 2019.

Chapter 4 : Results and Discussion – Demographics

This chapter gives descriptive analysis of the demographics of the 657 respondents to the questionnaire. All 657 responses were complete and valid. The analysis examined the profiles of geographic location, ethnicity, gender, age, schooling and qualifications at secondary and tertiary level. The purpose of the chapter is twofold:

- Firstly to show that the target population provided responses that are representative of the UK geographic and ethnic spread and represented or highlighted the skewed aspects of the population who study physics. In this way the efficacy of the data is confirmed.
- Secondly a number of lenses for the purposes of analysis are defined.

4.1 Geographic and Ethnic Spread

Table 4-1 and Table 4-2 of population demographics show that the data collected was representative of the population distribution of each country in the UK. Using the open access to the questionnaire through online portals however did collect 3.6% of responses from people educated outside the UK. Column 2 in Table 4-1 gives the percentage out of total responses for each country in the UK. Taking only UK educated respondents, column 3, shows that the proportions of responses from each UK country are in line with the populations of each country column 4 and therefore representative of the education of physics in each country.

Table 4-1: Response Distribution and Reach

Replies	% Replies	% UK only Replies	% UK Population/ Country (O.N.S 2018)
England	84.3	88	84
Scotland	6.2	6.4	8.2
Wales	3.8	3.9	4.7
N. Ireland	1.9	1.9	2.8
Non - UK	3.6		

Table 4-2 shows the ethnicity split among respondents in Column 2. Whilst in Column 3 gives the ethnicity split for England and Wales from Government figures (2011). Note that the ethnicity split among respondents is in keeping with the ethnicity spread throughout the UK. However literature points to the fact that ethnic minorities are underrepresented in physics, (section 1.1.4). The Office of National Statistics (ONS) does not publish census data on A level or degree level achievement by ethnic groups and therefore the IOP commissioned a study to investigate patterns of ethnic-minority participation using the data of the Youth Cohort Study (Cheng. Y, Payn. and Witherspoon. S 1995) and (IOP 2012b).

The Youth Cohort Study comprises the data for English and Welsh students only. The resultant RSC and IOP report, Representation of Ethnic Groups in Chemistry and Physics (Elias, Jones and Mc Whinnie 2006) shows the proportion of students studying physics at undergraduate level, column 4. Comparison of column 2 (ethnic spread among respondents – predominantly STEM graduates) and column 4 (ethnic spread among physics undergraduates) shows that the respondents' ethnic spread reflected the take up pattern of physics at university level with the predominance of white students and the higher portion of Asian and Mixed race students compared to the Black minority.

Table 4-2: Responses per Ethnic Group

Ethnicity	Respondents (%)	England & Wales (UK. Government 2011) (%)	Physics UG in UK (RSC. and IOP 2006) (%)
White	93.8	86.0	89.9
Black	0.3	3.3	0.8
Asian	3.8	7.5	5.6
Mixed	2.1	2.2	3.7

4.2 Gender Ratios

For the 657 responses 97% of respondents declared their gender. Of those 51.7% were female. Consistently throughout the two recent decades relevant to this research, the percentage of female students doing A level physics has remained constant at 20-21% (Section 1.1.1). The questionnaire response of 51.7% female is therefore important. For the purposes of the research it gave an equal voice to female as well male respondents. This level of response gave significance to identifying the influences and challenges faced by both young male and female students in their decision to study physics at post 16yrs. This 51.7% female respondents may be considered a sampling bias of an academic elite of female students and therefore a limitation of the study, however the results in Chapter 8 show that this female group did convey the likely experiences of the unrepresented females in physics.

Examining how this positive level of female response may have come about, Smith (2008) cites the work of Curtin et al. (2000), Singer et al (2000) and Moore and Tarnai (2002) and concludes that women are more responsive to questionnaires than their male counterparts. In addition literature on gender differences in STEM career aspirations (Rounds, Su and Armstrong 2009) assigns a greater "dispositional interest" (Rounds 1995) among women to people-related careers and environments and therefore females may be more inclined to contributing to the 'solution' of encouraging more young women to study physics and hence they acted out of responsibility to the questionnaire.

Further, the opening paragraph in the questionnaire stated the aim of the research, "to encourage more young people to consider studying physics post compulsory provision", this may have resonated with women's dispositional interest in people and their own interest in STEM, and so influenced their increased response to the questionnaire.

The current trend among STEM stakeholders, the UK Government, EU and US policy is to promote programmes which aim to increase the promotion of women and girls in STEM. For example the UK Government paper Women and Girls into STEM (2013) and the case made by Fatourou, Papageorgiou and Petousi in their paper on European policies and incentives (2019).

Women in STEM want to be heard now and correspondingly in the past two decades the number of organisations promoting and supporting women in STEM has grown. This includes organisations such as: WISE, WES, STEMettes, STEM pixies and Daphne Jackson Trust, for example. The number of Social Media Groups promoting women and girls in STEM have also proliferated on Twitter, some examples: @WomeninSTEM, @IETWomenNetowrk @STEMWomenUK, @steminist, @Science_Grrl

4.3 Age Range

Figure 4-1 shows the age distribution for respondents. Each age category was checked for its gender ratio. The level of response was expected to reflect access to the questionnaire.

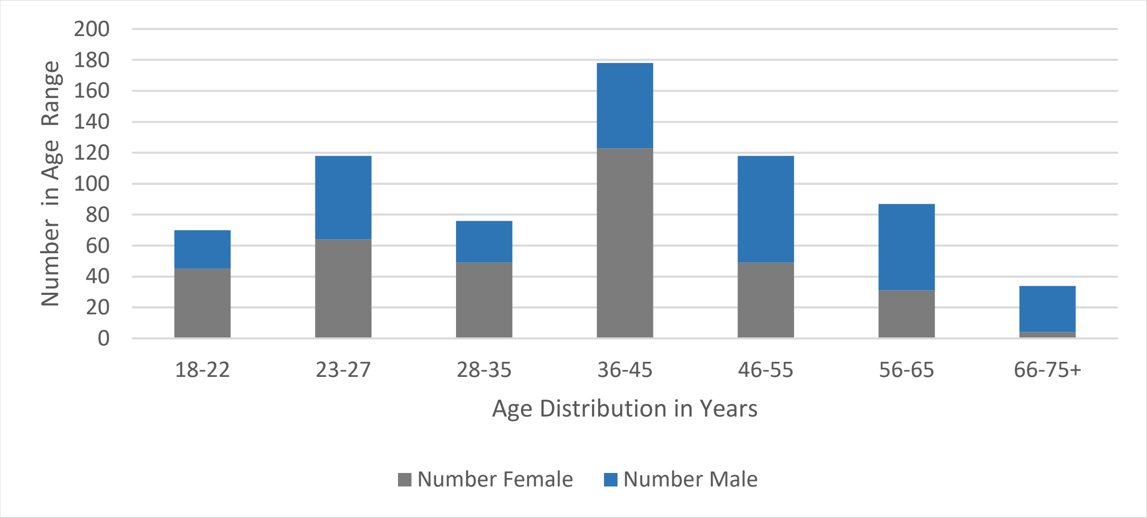

Figure 4-1: Age and Gender Distribution

The choice of age ranges are explained in the Questionnaire Design Section 3.9.2.2. Note that the highest response levels are in the 36-45 yr age range -- respondents in this age range are most likley to be in stable, establised employment and linked to physics related associations and organisations such as the IOP and the various engineering bodies such as IET, IMechEng and ICE. Through these networks they were most likely to have had access to the questionnaire.

The dip in numbers in the 28-35 yrs age range is curious; this total is 49 female vs 27 male. There may be some correlation here to the work reported by Round (2008) assuming that sign up to forums on social media follows the same pattern as female to male questionnaire response rates.

As might be expected the 65yrs + age range has fewer respondents as retirement may cause people to leave the networks and therefore access to the questionnaire.

4.4 Education

4.4.1 School Type

The types of schools attended by respondents were compared to the UK wide spread in school types. Overall the data shows bias when investigated against type of schools attended by those who studied A level physics.

Table 4-3: Percentage Spread for School Type

School Type	Response (%)	UK Figures for Attendance at each School Type.
Comprehensive	45 %	93% attend state funded of which 87% are Comprehensive (2018) Comprehensive schools were introduced in the 1960 and were fully established by the 1980s
Grammar	30 %	35%-25% 1944-1970 Sharp decline 25% -7% from 1970-1975 5% by 2019 (*Grammar Schools in England* 2019)
Independent	24 %	7% (*ISC Census and Annual Report* 2019)
Home Schooled	2 %	0.7% (Foster and Danechi 2019)

The schools attended by respondents reflect the school system biases already documented in literature for uptake of science and physics. That is, these figures reflect the fact that 75% of A level physics students attend only 24% of state funded schools (Comprehensive + Grammar).(UK. Government 2016); (2018)

A much greater proportion of the respondents compared to the national average, attended Grammar or Independent Schools. A greater proportion, 2% of respondents, (data only exists as a national figure for England) were home schooled. The 0.7% of the school population for England who are home schooled also includes children with special needs.

The proportion from Single Sex schools is disporportionately high. 27% of respondents reported attending a single sex school, 17% of whom attended All Girls Schools. Single Sex Schools make 25.5% or the independent sector and just 12% of the state sector (*ISC Census and Annual Report* 2019) .

Looking more closely at the results on single sex education, for those respondents who qualified in Physics at the Higher Education level, identified as Physicists in Table 4-4, the data showed the interesting result that 63% of female physicists attended a single sex school compared to just 15% of male physicists. As the number of single sex schools has been in decline in recent years this may account in part for the reduction in the percentage of females studying physics.

Table 4-4: Percentage of All Respondents who Attended Single Sex Schools Compared to the Percentage of Physicists.

Percentage of Respondents who Attended Single Sex Schools			
Gender	All 657 Respondents	Physicists	Physicists 18-27 yrs
Female	31%	63%	34%
Male	21%	15%	4%

Note that over the period of the research study (age 18-75 years, corresponding to years 2016 – 1963), the number of pupils attending independent schools doubled to the current level of 7%. In the same period the number of pupils educated in state grammar schools fell from around 20% to 5% (England and Wales). This means that over the period of this study, an increasing number of those who continued to study physics at university would have attended an independent school.

4.4.2 A Level Attainment

Data from Questions 7 and 8, on examination grades at age 16 and 18years are presented in Figure 4-2 which shows the spread in grades at GCSE/O Level and A level for all respondents. The GCSE/ O Level grades are on the left of the chart for comparison with A level grades on the right hand side.

A Level grade allocations are those reported by respondents in the range A*-F and where number grades of 1-9 were used for different boards or Baccalaureate, these were converted to an A-F grade according to a conversion table, UK Government education and skills report and The Waddell Report (2003; 1978).

Features to note are:

- The spread of grades achieved for the younger females, age 18- 35yrs is narrower than for males; A*,A,B compared to A*,A,B,C,D. Therefore of those reporting as female studying physics are achieving a higher proportion of the highest grades A*A,B.
- The spread of grades at A level is greater than at GCSE/O Level: A-F compared to A-D. The IOP in their research also report on this finding, Section 1.1.2.
- For students achieving the highest grades at age 16yrs, a smaller proportion achieve the highest grades at A level compared to all other subjects. (IOP 2010) This was also discussed in Section 1.1.2

- Older males (over 46years) who would have taken the O Level examination have assigned themselves A* when this was not an available grade for the O Level/A level examination of that time. Fewer women in the age range 36-75years achieved the highest grade of A or its equivalent in the exam system of the time. This discrepancy presents an example of inflated, positive self-assessment among the males. Betz and Hackett (1981) have described this trait in men in relation to career expectations.

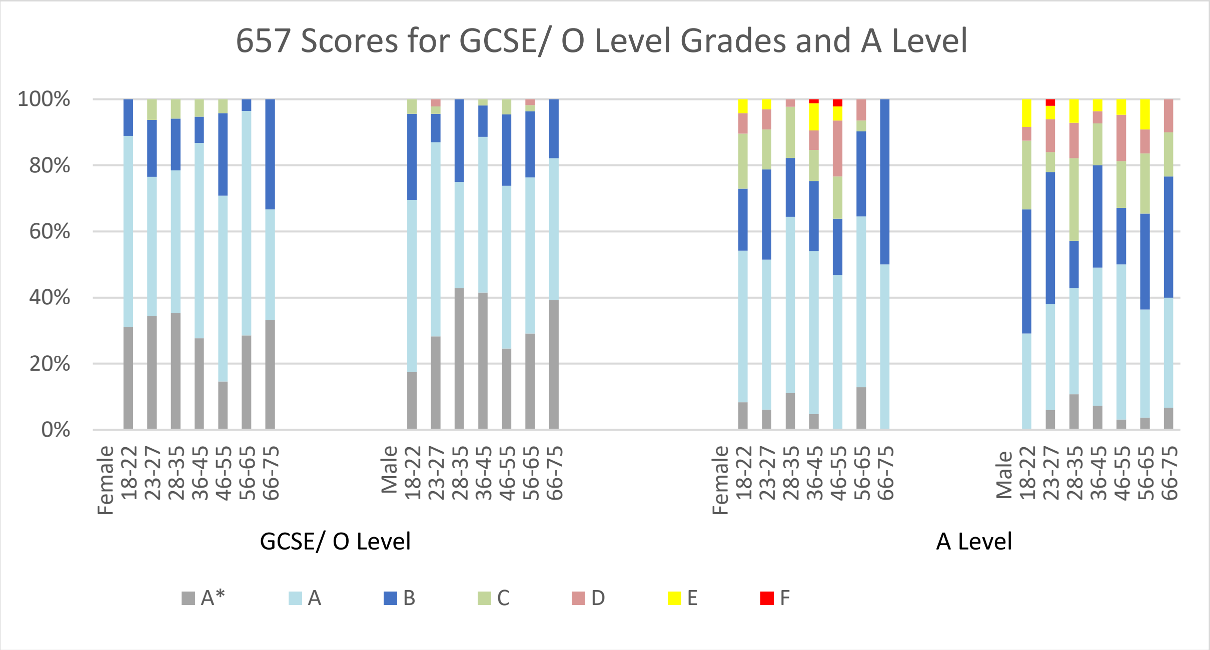

Figure 4-2: Comparing Achievement at GCSE with A Level.

In the group aged 66-75yr for females there were only 4 members so the results are not statistically significant. Only 3 gave their O level results and all four gave their A level grade.

Table 4-5: Grade Distributions Related to Gender at GCSE/O Level and A level

Grades	A* A	B	C	D	E	F
GCSE/O Level – Percentages						
Female	81.9	13.9	4.1			0.3
Male	79.5	17.4	2.3	0.7		
A Level - Percentages						
Female	54.9	21.4	11.8	7.1	4	0.6
Male	42.1	28.8	14.7	8.8	5.2	0.3

The same analysis for the subset that continued with their physics studies in third level education, the Physicists, show further differences. Note the female entry for GCSE age bracket 66-75+ with only 3 entries all at grade A so not a representative sample. By contrast there were 27 males in this age group.

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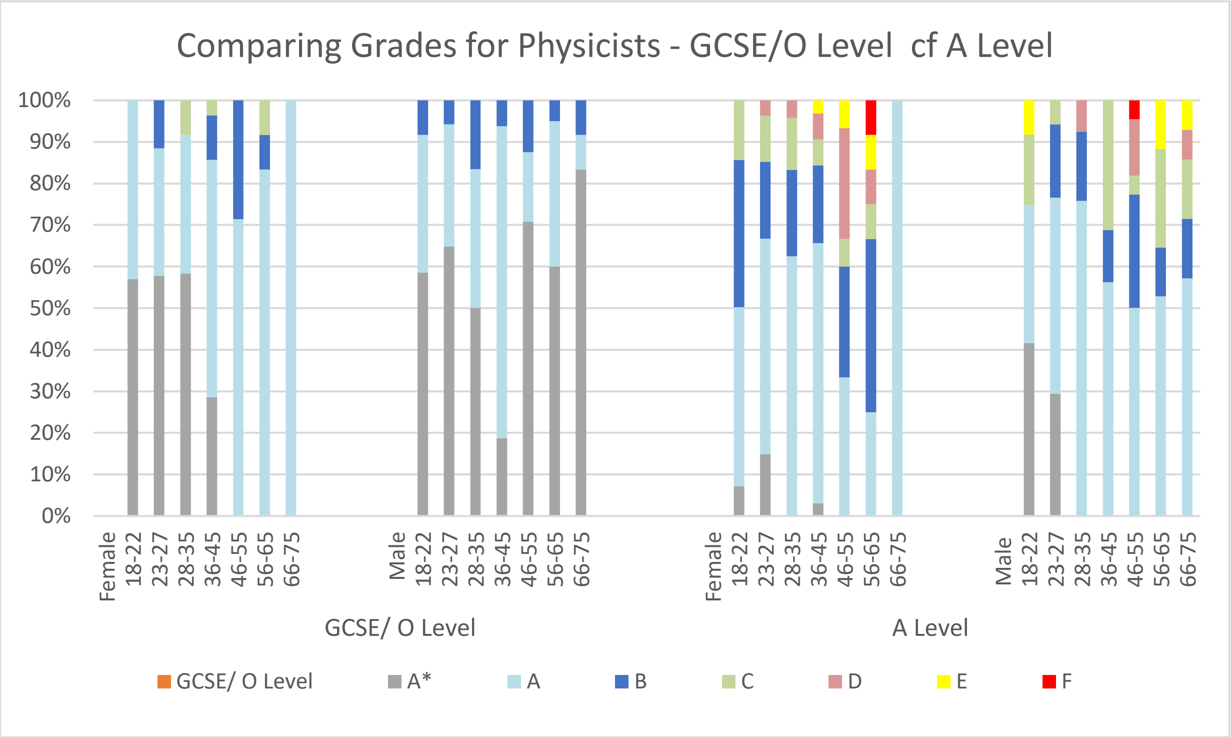


Figure 4-3: Physicists – Grade Distribution for GCSE/ A level and O Level/ A level

Table 4-6 GCSE/ O Level Grades for Physicists. Summing the A and A grades*

Grades	A* A	B	C	D	E	F
GCSE/O Level - Percentages						
Female	85.9	10.7	1.7			
Male	80.5	15.0	4.4			
A Level - Percentages						
Female	55.1	23.6	9.4	7.1	2.4	0.8
Male	62.2	14.4	13.5	4.5	4.5	1

Table 4-6 shows that: both males and females who had continued to study physics had achieved the highest grades, mainly A*,A, B at GCSE/O Level.

Compared to the total population of respondents, the performance at A Level for physicists was higher with fewer in the grade range D and E, compare Table 4-5 to Table 4-6. Note again that the older males (46years+) reported achieving an A* grade at O Level which was not a possible grade. Females of this age only reported grade A. However at A level the A* grade is not claimed among physicists unlike in the total respondent population.

Table 4-7: A Level Grades by gender according to GCSE vs O level cohorts

Female	%A*A	%B	%C	%D	%E	%F
GCSE	89.2	8.6	1.1			
O Level	75.0	21.4	3.6			
Male	%A*A	%B	%C	%D	%E	%F
GCSE	91.2	8.2	0			
O Level	69.6	21.4	8.9			
Female	%A*A	%B	%C	%D	%E	%F
A Level	62.5	21.8	10.4	4.2	1.0	
O/A level*	32.1	32.1	7.1	17.8	7.1	3.5
Male	%A*A	%B	%C	%D	%E	%F
A Level	71.9	10.5	14.0	1.75	1.75	
O/A Level*	51.9	18.5	12.9	7.4	7.4	1.9

Table 4-7 gives further breakdown of the male and female groups into those who would have studied for the O level examination, i.e. those aged 46yrs+. This shows that the percentage of physicists achieving the highest grade A at O level was significantly lower than the percentage of A*A at GCSE, ~70% compared to 90% for both male and females. The attainment for each gender is however the same. By contrast at A level, the difference in attainment of A grade persists for those over 46yrs of age, however it differs by gender with 30% lower for females and 20% lower for males. This overall trend of greater numbers of students achieving grade A since the introduction of the GCSE (in all subjects) is well documented and debated and is in keeping with changes in grade boundaries and curricula changes of the 1980s that brought about improvement in attainment for girls over this period (McNally 2005).

For the O level cohort, ~30% of females achieved grade A compared to ~50% for males. Social scientists attributed differences in male and female attainment in this period to differences in aspiration and expectation of females. (Francis 2002; Schoon and Eccles 2014) Considering that the number of male and females in this physicists group are equal at Degree, Masters and PhD level, the gender difference in attainment among the 46+yrs group suggests some positive male bias in the examinations of the time, or again these are the reported grades rather than actual grades achieved according to government figures in which case the males are imagining that they achieved a higher grade than in reality.

White and Langer (2009) in their research with 3,600 students in US schools, found that girls excelled in mathematics yet achieved lower than males in physics. Therefore White and Langer posed the suggestion that female students are victims of Stereotype Threat, a phenomenon which causes people to score lower when this is the expectation. Either way this does show the importance of attainment in shaping the physics identity. This theme is explored in Chapter 7.

4.4.3 Higher Education Qualifications.

Questions 9 and 10a asked for respondents' further study beyond A level, naming the degree subject. 98.6% of respondents were graduate level qualified, largely STEM with 1.8% non-STEM. Engineering and Physics degrees made up almost 70% of responses; Physicists 37% and Engineers 31%. The degree subjects have been grouped in broad categories as shown in Table 4-8. All of these categories are subjects studied at A level except Engineering, for which Physics is the direct entry qualification. The distribution of respondents among these categories is given in Figure 4-4. Note Chemical Engineering is listed under Chemistry, as there were only 6 repondents with this degree subject, and only 2 out of the 6 lisiting their career (Q11) as Engineering/Technology/Manufacturing, therefore based on the majority response, the Chemical Engineers were classed under the Chemistry category.

Table 4-8: Degree Categories

Degree Category	Consisting of.
Physics	Physics at Undergraduate, Masters and PhD level
Engineering	Civil, Electricial , Electronic, Aerospace, Aeronautics, Nuclear, Manufacturing, Product Design, Motorsports, Automotive, Bio-Medical
Chemistry	Chemisty, Chemical Engineering, Colour Chemistry, Polymer Chemistry
Biology - Life Sci - Medical	Biology, Phamacology, Marine Biology, Immunology, Microbiology, Botany, Physiology, Biochemistry, Bio-Medical Science, Medical Bio-Chemistry, Zoology. Biological Sciences, Cell Biology Medicine/Vet Med/Dentistry
Mathematics	Mathematics, Maths+Economics, Maths+ Philosophy, Maths+Computing, Statistics,
Geography	Geography, Geology, Earth Science, Environmental Engineering
Computing	Computing, Programming, Software Engineer, Technologist
Non-STEM	Music , Law , History, Education, Management, Recreation, Undefined

The questionnaire was distributed widely through social media portals and STEM stakeholder orgainsations to attract responses from a wide audience of past physics learners from across the career spectrum. However very few non–graduate responses were obtained and with hindsight this may be because the portals were predominantly graduate focused.

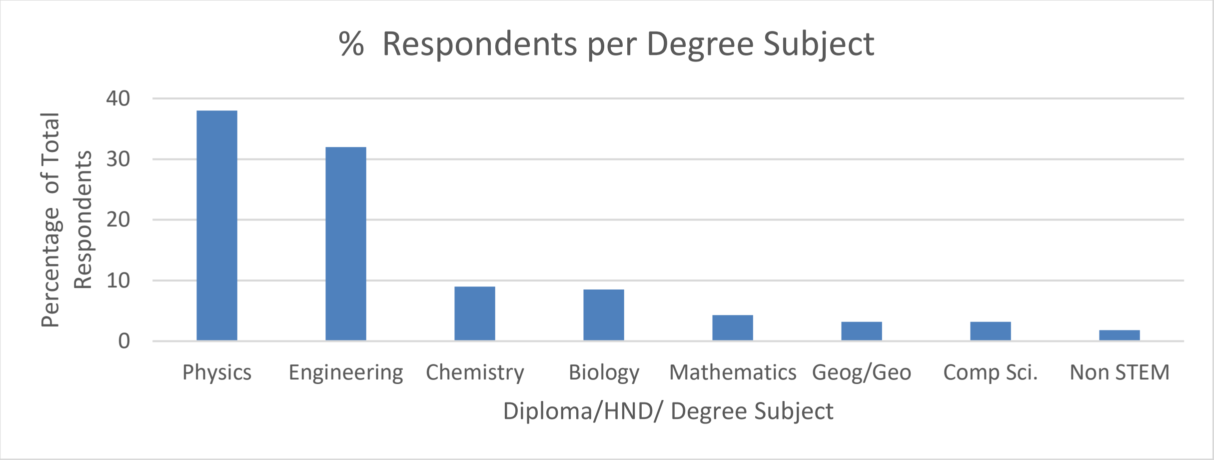


Figure 4-4: Higher Qualifications According to Degree Subject Category

Smith Moore and Tarni (2002) and Goyder report that questionnaires have a higher response in general from more educated and more affluent people. This may explain why returns in this study were almost exclusively graduate level educated (98.6%), with the remaining 1.4% being 66% at HND level and three replies with no Higher Education qualification recorded. Since this was an online questionnaire, the high graduate response may be explained as follows:
Graduates are more likely to belong to the professional bodies which were among the routes through which the questionnaire was circulated.

Responses may be biased to those who feel that they did succeed in physics or STEM. Others may not consider their A level physics grade level as success. The questionnaire opens with this statement “success in physics” and this may have halted some respondents. Most Respondents, 74% had grades A*, A or B at A level physics. People with such high A level grades typically go on to graduate from university.

The respondents although openly accessed are coming through portals that are already self-selective groups i.e. those already passionate or interested or working in education or promoting STEM/Physics or are women in STEM. Although this may count as a biased and certainly non-random selection in the study, yielding a skewed response, for the purposes of this study this response was considered positive and amounts to a controlled variable for data analysis. In this control the respondents are ideal in that they are committed enough to give the questionnaire their time and their responses may have been considered and thought through or debated at a previous occasion and therefore any depth of knowledge or analysis has been brought to bear. This could be considered a negative aspect if these respondents spent longer on questions to deliver their views. Since this was anticipated and so respondents were asked to not overthink their responses but to reply promptly. This was an attempt to put respondents on an equal footing. A breakdown of those who continued with physics beyond A level to tertiary qualifications shows that for this cohort of respondents, the number of male and female respondents at each level was comparable. This is useful for the analysis of results, comparing male vs female as a controlled group with equal levels of qualification.

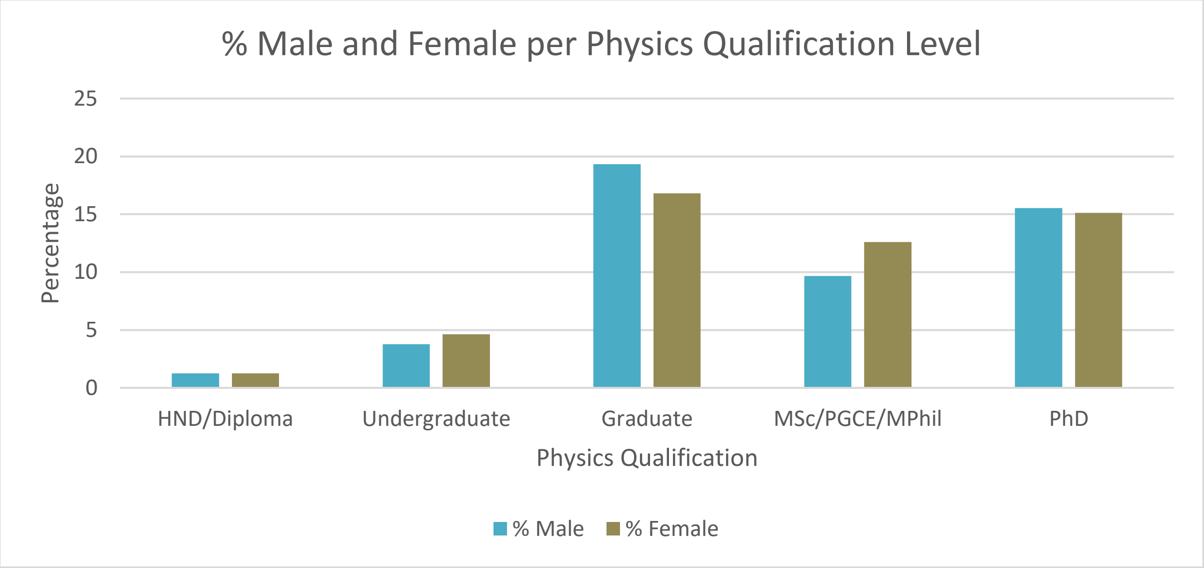


Figure 4-5: Female to Male Ratios for Physicists at Each Higher Qualification Level

4.5 Summary - Demographics

The geographic spread for where respondents had been educated at secondary school level, was representative of the population distribution of the UK. The ethnic spread was representative of the ethnic spread among Physics graduates where the representation is predominantly white and Black students are under-represented. Response levels for the full age range (18-75+) showed a normal distribution pattern with a dip for the 28-35 age group which was difficult to suggest why this might be the case.

School types were skewed well above average towards, independent and grammar schools and single sex schools. In the case of females who went on to study physics at degree level, two thirds of the older 46yrs+ cohort attended all-girls schools and one third of the younger 18-45yrs cohort.

Respondents were 98.6% graduate level, 98% STEM educated and 37% were physics graduates and 31% engineering graduates. Of physics graduates, at every qualification level the number of females respondents were comparable to the number of males, which is considered to be an important feature in validating the female experience in a male dominated subject that is typically 80% male and 20% female.

Chapter 5 : Results and Discussion – Physics Competences

This chapter presents and discusses results for questions Q13-17, where each of the five Physics Competences described in total by 46 indicators are assessed to address Research Question1 *How can a set of Physics Competences be developed and can a Scale of Mastery be defined to determine a threshold to success in physics.*

Data was analysed in Excel and SPSS in five stages. Stage 1 presents an overview of the whole population of respondents' use of the scale of mastery. Stage 2 develops the distribution and metrics along the Mastery Scale. Stage 3 presents an assessment of the scale on its differentiation of A level grade attainment. Stage 4 explores the ranking of Indicators according to the demands of mastery while Stage 5 uses a correlation analysis to assess the inter-dependence of Indicators and Competences. The mastery of competences is then discussed for physicists compared to all STEM respondents and by gender before Stage 6 which is the statistical development of the Mastery Scale.

5.1 Mastery of Physics Competences Overview

Stage 1 Levels of Mastery

The results on mastery of physics competences from all respondents are shown in Table 5-1 and Figure 5-1. This descriptive analysis is colour coded to show the respondents' level of mastery according to the four point scale described in Section 3.3. Note that the scale Ease, Effort, Guidance and Challenge is not a linear scale but a ordinal scale, as discussed in Section 3.3. The scale was quantified by percentage frequencies. Indicators are shown on the horizontal axis with their full statements in the order they appeared in the questionnaire.

As a descriptive analysis Figure 5-1 shows the extent of the challenges of Physics Competences as assessed by the given respondent population. Logically indicators and competences most challenging to master are those with the lowest percentage levels of Ease and highest levels of Challenge. Figure 5-1 and *Table 5-1* show that the percentage frequency responses per indicator range from 12.9% to 55.9% for Ease, 38.7% to 60.4% for Effort, 4.7% to 30.4% for Guidance and from 0.9% to 11.9% for Challenge. These figures were used as a simple means of ranking the indicators from 'most difficult' to 'easiest' to master. Since the level of responses for Ease are much greater than for Challenge (reflective of the high percentage of high academic achievers in the respondent population) then using the Ease figures gave the more accurate ranking of the Indicators.

It could be debated that the Ease figures should be combined with the Effort figures, however this does not change the order of rank as it is the Ease figures which give the greatest discrimination (greatest standard deviation), while the Effort figures reflect what the greater portion of respondents could achieve without guidance. Table 5-2 shows the most distinct 'easiest' indicators while Table 5-3 shows the 'most difficult' indicators.

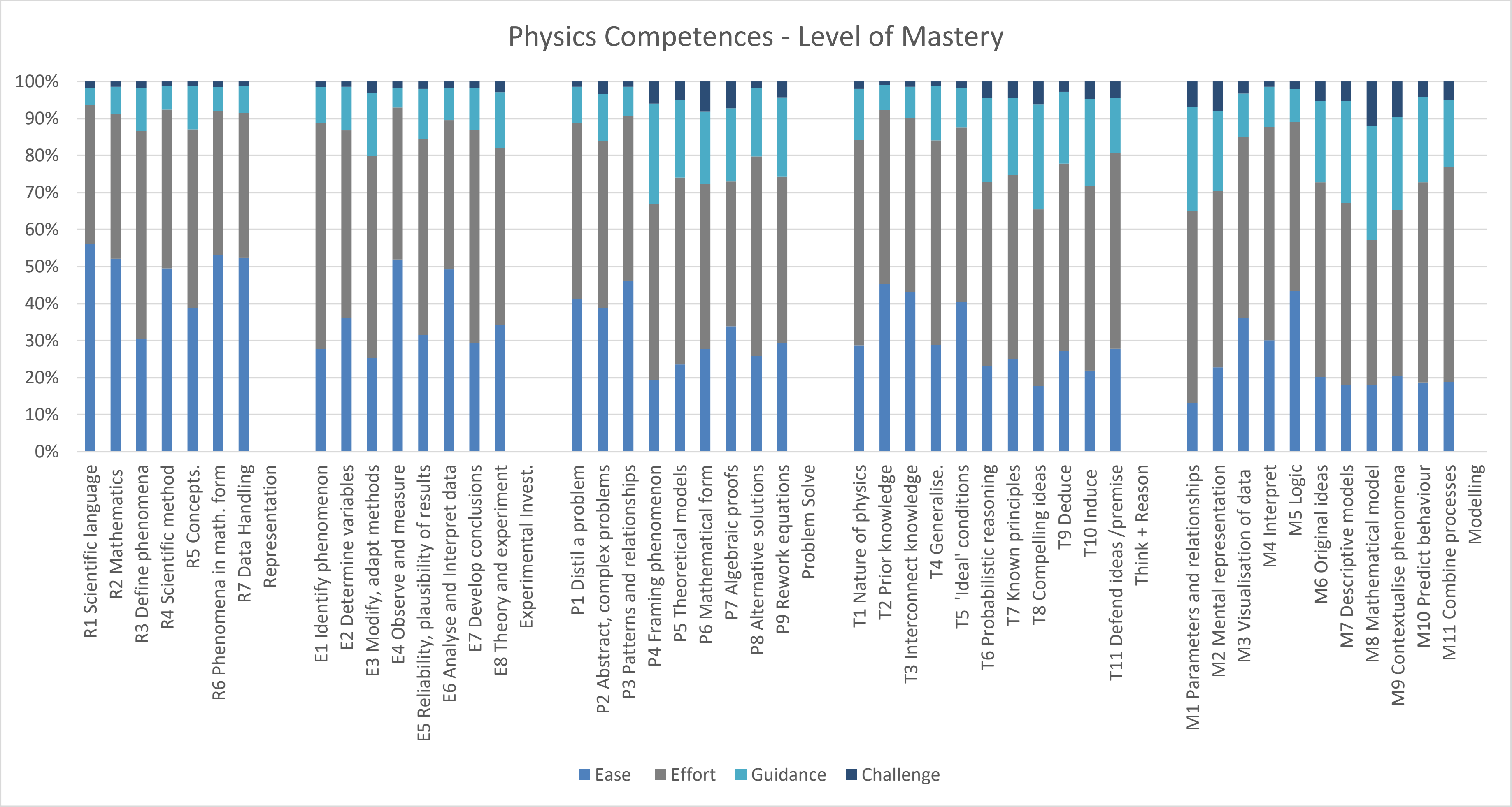


Figure 5-1: Physics Competence – Mastery Overview for All Respondents

Table 5-1: Percentage Response per level of Mastery for each Indicator.

Competence	Ease	Effort	Guidance	Challenge
R1	55.9	37.4	4.7	1.7
R2	52.1	38.9	7.5	1.4
R3	30.3	56.0	11.6	1.7
R4	49.0	42.5	6.4	1.1
R5	38.5	48.1	11.7	1.2
R6	52.8	38.8	6.4	1.5
R7	52.2	39.0	7.3	1.2
Competence	Ease	Effort	Guidance	Challenge
E1	27.5	60.4	9.7	1.5
E2	35.9	50.1	11.7	1.4
E3	25.0	54.0	17.0	3.0
E4	51.4	40.6	5.3	1.7
E5	31.2	52.4	13.5	2.0
E6	48.7	39.9	8.5	1.8
E7	29.2	57.1	11.1	1.8
E8	33.9	47.5	14.9	2.9
Competence	Ease	Effort	Guidance	Challenge
P1	40.9	47.2	9.7	1.4
P2	38.5	44.7	12.6	3.3
P3	46.0	44.3	7.8	1.4
P4	19.1	47.3	26.9	5.9
P5	23.3	50.1	20.7	5.0
P6	27.4	44	19.3	8.1
P7	33.5	38.7	19.5	7.2
P8	25.7	53.4	18.3	1.8
P9	29.2	44.6	21.2	4.4
Competence	Ease	Effort	Guidance	Challenge
T1	28.5	54.9	13.7	2.0
T2	44.7	46.4	6.7	0.9
T3	42.6	46.6	8.4	1.4
T4	28.5	54.6	14.6	1.1
T5	39.9	46.6	10.4	1.8
T6	22.8	49.0	22.4	4.4
T7	24.5	49.0	20.5	4.4
T8	17.5	47.0	27.9	6.2
T9	26.8	49.9	19.2	2.7
T10	21.6	49.2	23.3	4.6
T11	27.5	52.1	14.8	4.4
Competence	Ease	Effort	Guidance	Challenge
M1	12.9	51.0	27.5	6.8
M2	22.5	46.9	21.5	7.8
M3	35.5	47.9	11.6	3.2
M4	29.7	56.9	10.7	1.4
M5	42.8	45.1	8.8	2.0
M6	19.8	51.8	21.6	5.2

Competence	Ease	Effort	Guidance	Challenge
M7	17.8	48.4	27.1	5.2
M8	17.8	38.7	30.4	11.9
M9	20.1	44.1	24.7	9.4
M10	18.4	53.3	22.7	4.1
M11	18.6	57.2	17.8	4.9

Table 5-2: Indicators – Easiest i.e. Greatest level of Ease

	%	Percentage Frequency Ease + Effort
R1	55.9	Use technical and scientific language
E4	51.4	Accurately observe and measure
R6	52.8	Understand and explain phenomena represented as a diagrams, graphs, tables or in a mathematical form
R7	52.2	Communicate data and physics concepts as diagrams, graphs, tables or in a mathematical form
R2	52.1	Work with approximation, orders of magnitude, proportion, rates, exponentials etc.
R4	49.0	Apply scientific method and conventions

Table 5-3: Indicators – 'Most Difficult' i.e. Least level of Ease

	%	Percentage Frequency for Ease + Effort
M1	12.9	Distil complex and abstract phenomena to get to a set of parameters and relationships
M8	17.8	Create a mathematical model that describes the phenomenon or problem
T8	17.8	Develop compelling ideas and hypotheses
M7	17.8	Develop descriptive models to understand complex systems
M10	18.4	Use constituent parts to predict behaviour
M11	18.6	Combine the process of evaluation and adaptation to observations, reasoning, induction, deduction modelling, prediction and testing
P4	19.1	Create new ways of framing a problem or phenomenon

Inspection of the two sets confirms that the 'easiest' indicators are elements of Representation and Experimental Investigation Competences while the 'most difficult' indicators are the Thinking and Reasoning and Modelling Competences.

These appear in this order as the lower to upper levels of Bloom's taxonomy. However Bloom's taxonomy has been updated by Anderson and Marzano and this hierarchy removed. Also in keeping with the aims of this research to identify the competences demonstrated by physics learners, these indicators are better referred to in terms of the different types of competences; cognitive and procedural competences, (Section 2.1.1 and 2.1.2). Therefore Table 5-2 are the procedural competences while Table 5-3 are the higher demand cognitive competences as described by Eyre (2016a). As discussed at the introduction, this approach of defining competences for Competency Based Learning may have advantages for a subject such as physics and the details of these two tables are relevant to curriculum development .

Stage 2 Distribution and Metrics along the Mastery Scale

Plotting the mean frequency values for each competence, Table 5-4, produced the outlines shown in Figure 5-2, of which four of the five outlines are truncated two tail distributions. Representation is the exception and this is discussed on Section 5.3, Page112. For the four other outlines, it would be expected that a full two tail distribution would occur if a less high attaining, high ability group had responded and therefore the proportion of scores for Ease was lower. This confirms the mastery scale is a response scale calibrated to the respondent population.

Table 5-4: Mean Values and Standard Deviation Values for each Competence

	Ease	Effort	Guidance	Challenge	
St Dev	9.31	6.79	2.69	0.24	Representation
Mean	42.51	38.44	7.29	1.26	
St Dev	9.09	7.33	3.72	0.61	Experimental
Mean	32.43	45.48	11.46	1.86	
St Dev	10.39	13.74	6.99	1.74	Prob. Solve
Mean	29.40	42.80	16.30	4.02	
St Dev	8.95	3.08	6.67	1.78	Think+ Reason
Mean	31.51	49.57	16.54	3.08	
St Dev	8.99	5.57	9.13	3.16	Modelling
Mean	23.26	49.21	20.40	5.63	
Overall Mean	31.80	45.10	14.40	3.18	All Competences

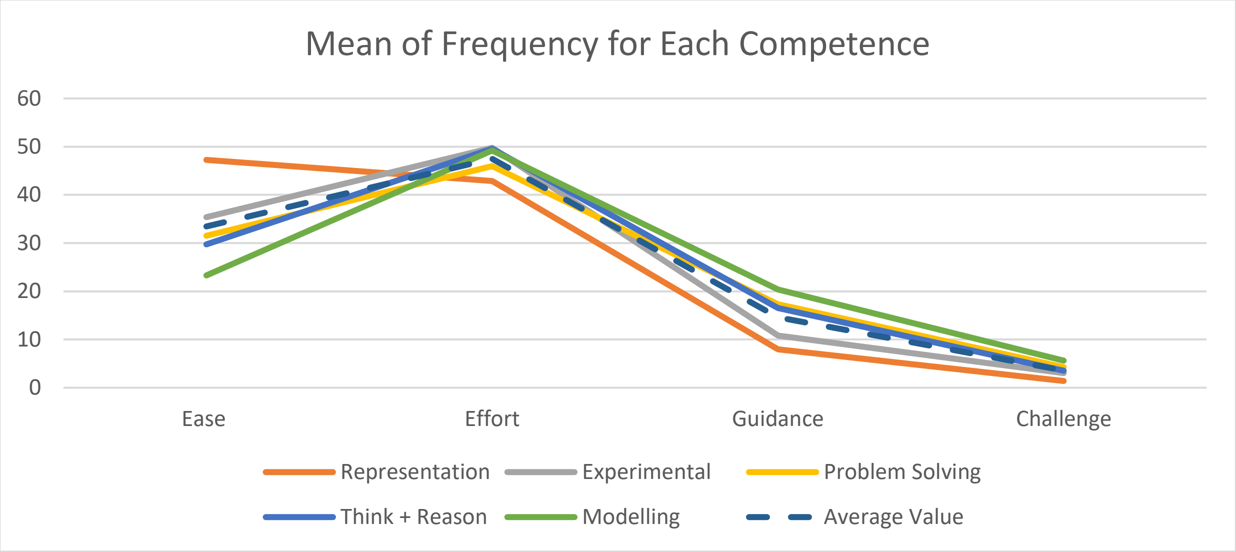


Figure 5-2: Distribution of Mastery per Competence.

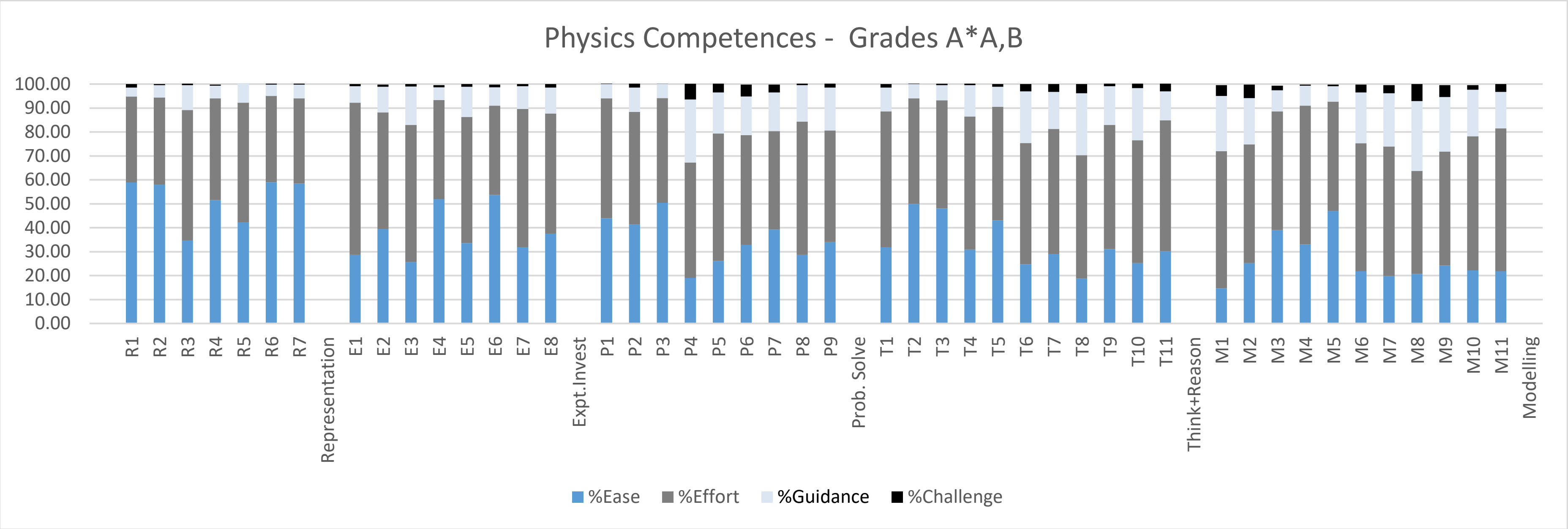
5.2 Physics Competence vs A level Grade Attainment.

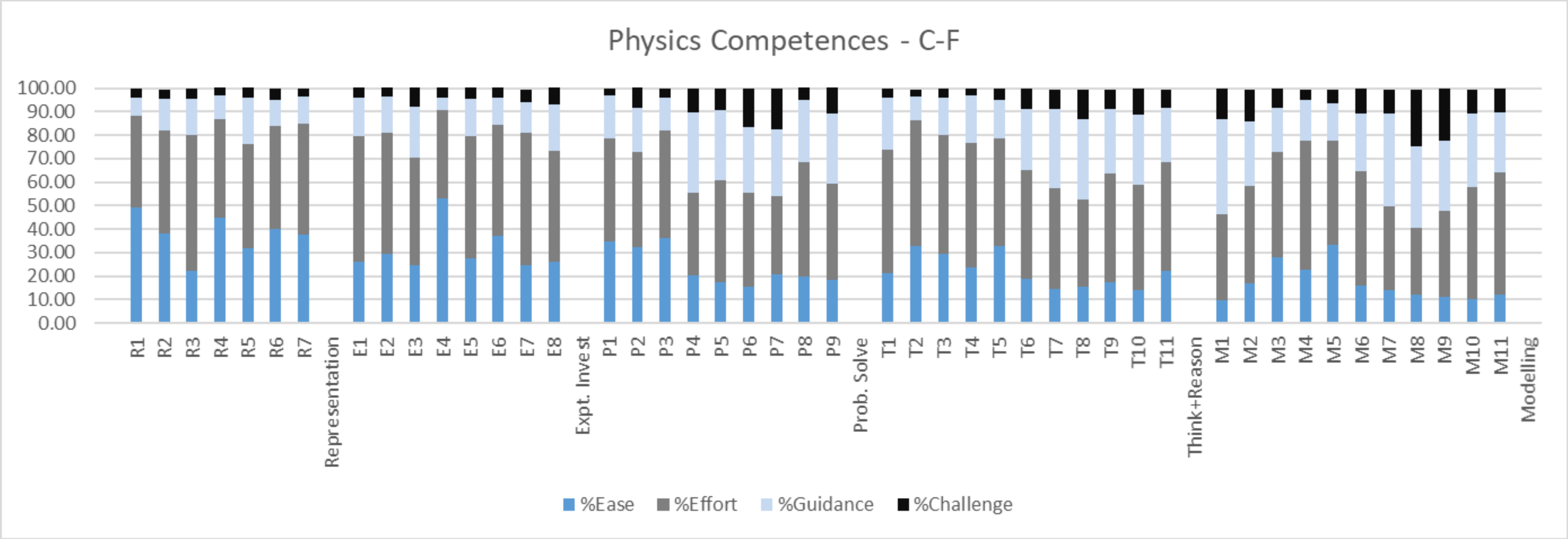
Stage 3 A Scale of Differentiation with A level Attainment

To explore the discrimination of the scale, this section examines mastery of physics for those respondents who achieved A level grades of A*, A, B compared to levels of mastery of those who achieved A level grades of C-F. These grade ranges were chosen for two reasons. Firstly 48.7% of all respondents achieved the A*A, B grades across the whole age range and therefore the population was effectively divided into two parts. Secondly university entrance criteria have risen over the six decades included in this study. Current university entrance levels for physics are typically A* and A or B. Therefore an overview of the responses are set out for these two groups Figure 5-4 and Figure 5-5 as shown on Page 102. Note that formatting the graphs did not allow the figure captions to be placed on page 102 but are given below, ordered as they appear.

*Figure 5-3: Physics Competence- Respondents with A*A,B at A level*

Figure 5-4: Physics Competence- Respondents with C –F at A level


Physics Competences - Grades A*A,B
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
R1
R2
R3
R4
R5
R6
R7
Representation
E1
E2
E3
E4
E5
E6
E7
E8
Expt.Invest
P1
P2
P3
P4
P5
P6
P7
P8
P9
Prob. Solve
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
Think+Reason
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
Modelling
%Ease
%Effort
%Guidance
%Challenge


Physics Competences - C-F
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
R1
R2
R3
R4
R5
R6
R7
Representation
E1
E2
E3
E4
E5
E6
E7
E8
Expt. Invest
P1
P2
P3
P4
P5
P6
P7
P8
P9
Prob. Solve
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
Think+Reason
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
Modelling
%Ease
%Effort
%Guidance
%Challenge

This descriptive analysis shows that the scale does differentiate mastery of the Physics Competences with academic attainment. Those with lower grades C-F do indeed show greater levels of Challenge and lower levels of Ease per indicator. The mean frequency values for each scale level, for the two attainment groups A*A,B and C-F is shown below in Table 5-5.

Table 5-5: Mean Response values for Ease, Effort, Guidance and Challenge for each Grade group.

Grade Groups	Ease	Effort	Guidance	Challenge
A*, A, B	36%	49%	12%	2%
C-F	26%	45%	26%	8%

In analysing the data it is useful to consider that respondents who chose the Ease and Effort scale levels were self-sufficient and able to master physics, according to their own assessment. Those who chose Guidance or Challenge were aware that their learning required support. Considering that the majority of respondents achieved high academic success, it is important to note that either route, Ease/Effort vs Guidance/Challenge can achieve a successful academic outcome.

In the case of the C-F group, 34% fell into Guidance and Challenge levels compared to 14% for the higher achieving group. Such measures of scale are useful in terms of the highlighting the needs in pedagogic support for students who would compare to this cohort of C-F graders. Therefore it was important to take the analysis to the next stage to look at the individual competences and the indicators within, in respect of these two groups. In this way the areas for pedagogic support could be defined more specifically. How the individual competences rank with the two grade groups A*, A, B and C-F, are shown in Figure 5-5 and Figure 5-6.

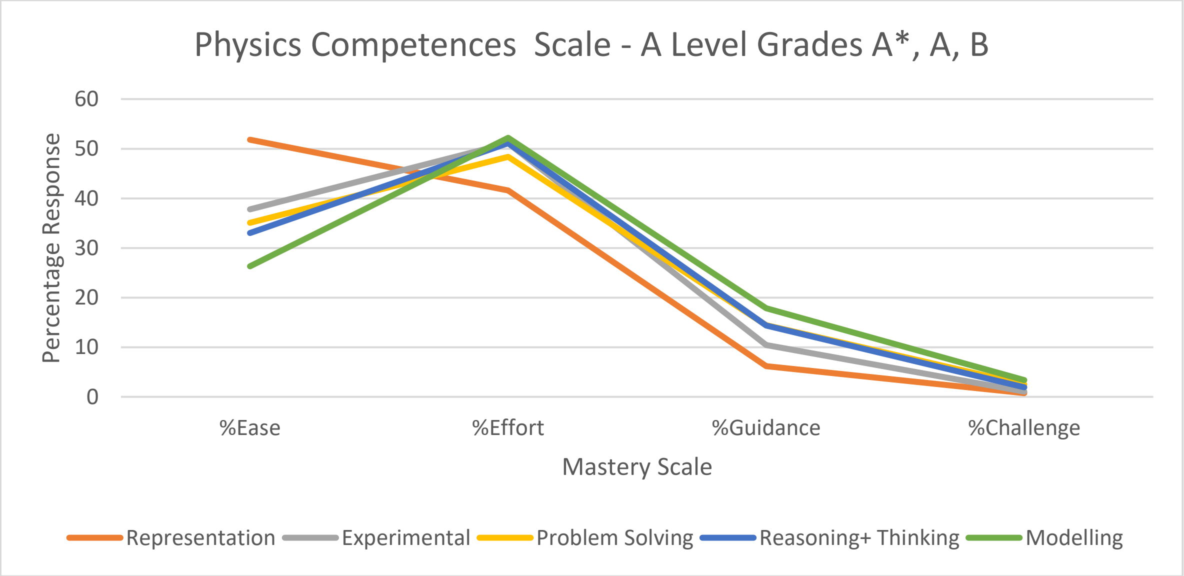


*Figure 5-5: Physics Competences Scale for A*A,B Attainment*

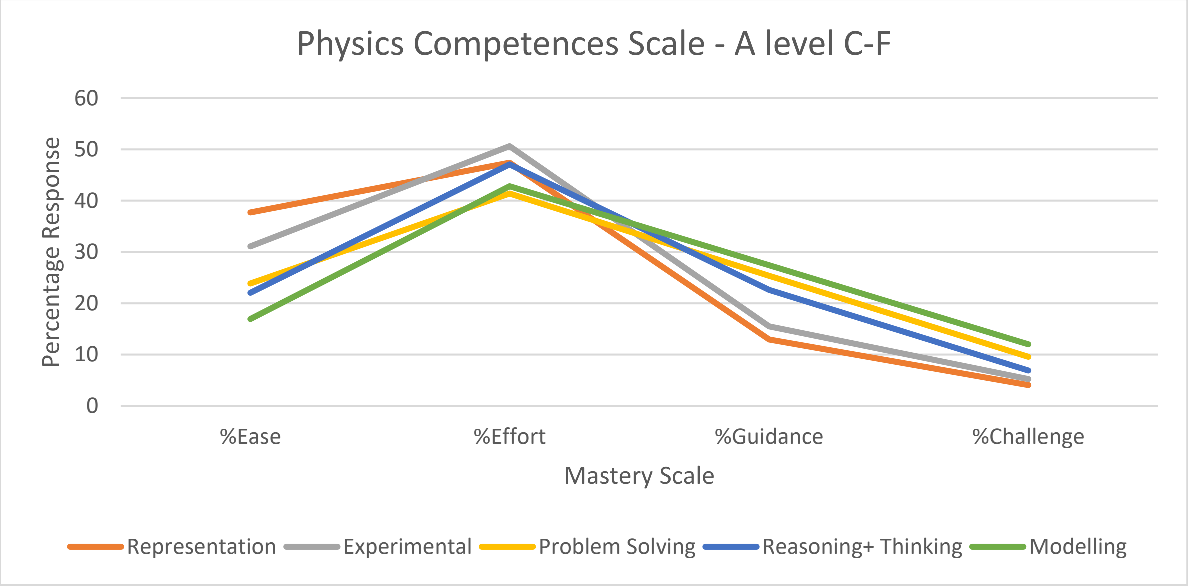


Figure 5-6: Physics Competence Scale for the Lower Attainment Students

Note the most outstanding feature between the two groups was that the Representation competence does not follow a two tail outline for the A*A,B group. This distinguishing differentiator is discussed later, page 112. For all competences the C-F grade group showed broadening of the curve due to some indicators requiring greater than a typical amount of effort to master, they were deemed to be challenging.

In both grade groups, using the Guidance and Challenge levels, the competences are ordered in levels of increasing difficultly from Representation, Experimental Investigation, Problem Solving, Thinking + Reasoning and Modelling respectively.

5.3 Which Competence Indicators Most Challenge Student Learning.

Stage 4 Ranking Indicators According to Levels of Mastery Demand.

Progressing from the comparison of the grade groups for all Physics Competences, Figure 5-7 to Figure 5-11 show how A*A,B group compare with the response of the C-F group for each set of Indicators. The salient features in this comparison are:

- The broadening of the curves for the C-F group.
- Branching of the sets of Indicators into two levels of relative difficulty.

This overview provided some useful insight relevant to curriculum development and pedagogy and therefore the frequency data are further examined in Table 5-6 to Table 5-15 and discussed thereafter.

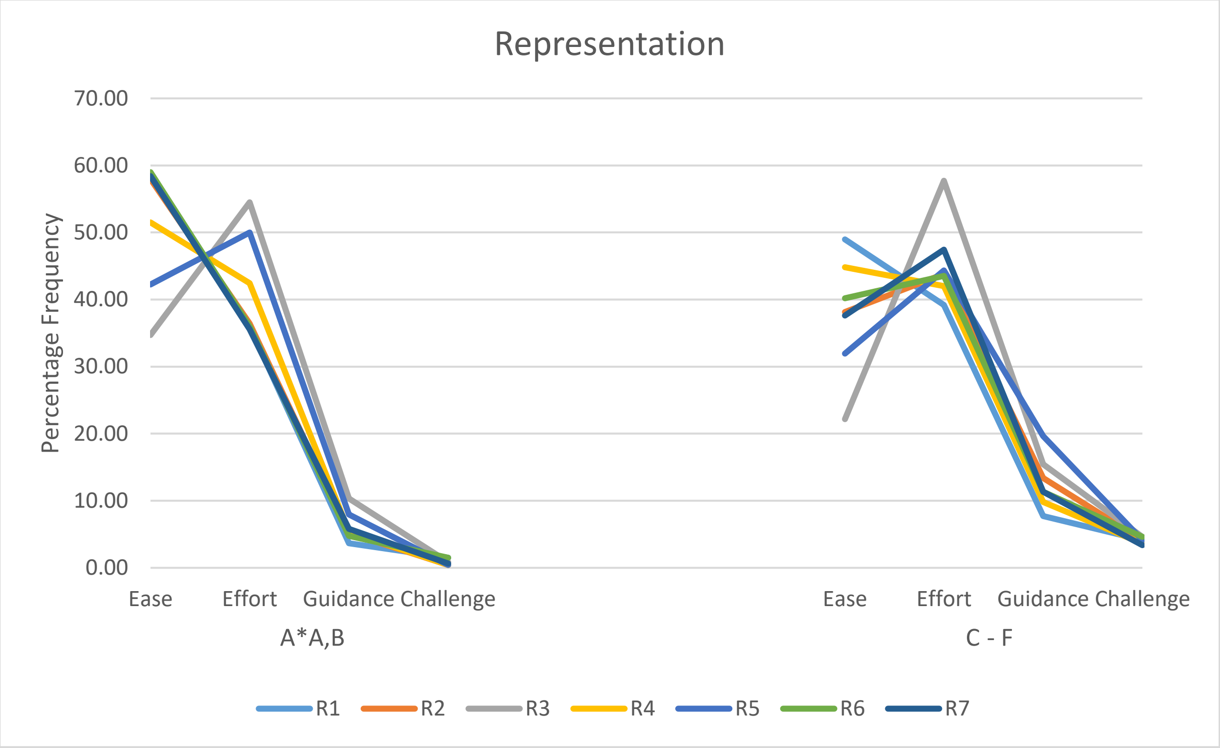


*Figure 5-7: Representation: Comparison grade groups A*AB, C-F*

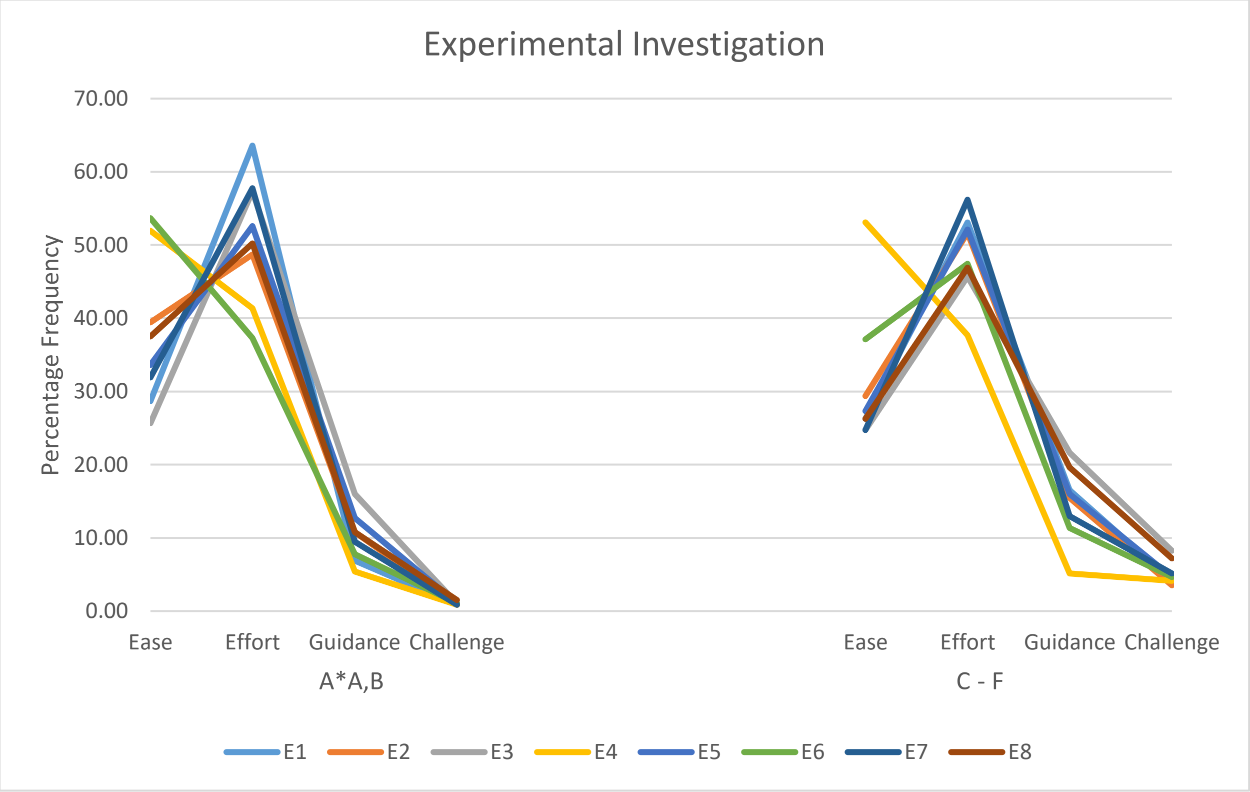


*Figure 5-8: Experimental Competence: Comparison grade groups A*AB, C-F*

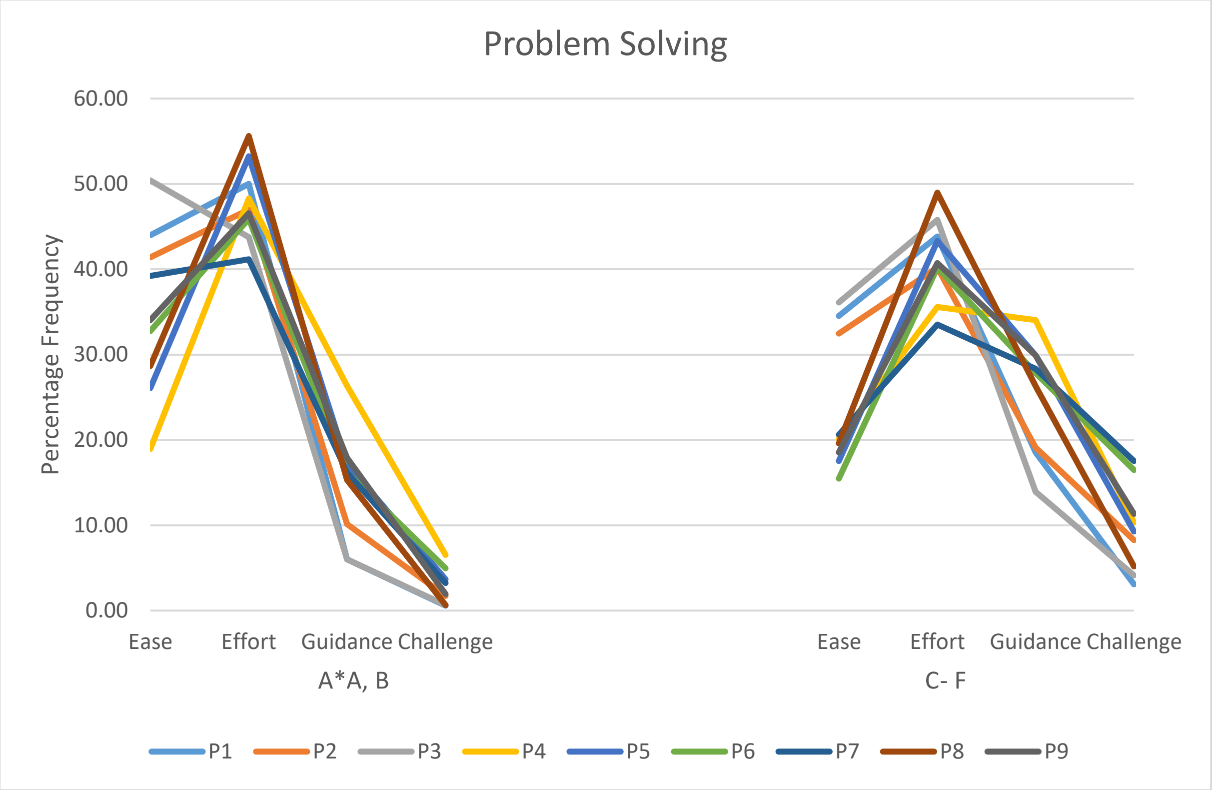


*Figure 5-9: Problem Solving: Comparison grade groups A*AB, C-F*

*Figure 5-10: Thinking + Reasoning: Comparison grade groups A*AB, C-F*

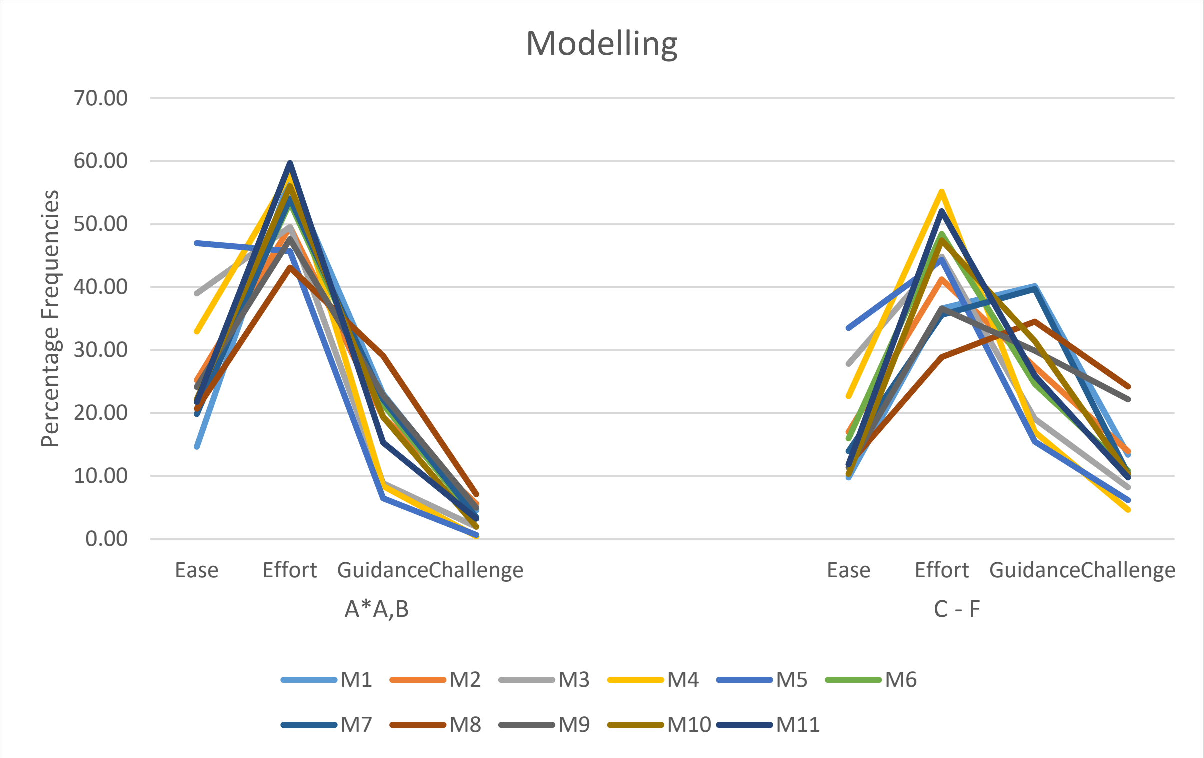


*Figure 5-11: Modelling: Comparison grade groups A*AB, C-F*

In Tables 5-6 to 5-15 the percentage frequency values are shown with the Indicators reordered to rank from least to most difficult to master, according to the level of Ease value for the A*AB set. For each competence the 'easier' to master Indicators are highlighted blue.

Mastery of Representation

*Table 5-6: Representation – Ordered easiest to most challenging by A*AB group.*

	%Ease	%Effort	%Guid.	%Chall.		%Ease	%Effort	%Guid.	%Chall.
	A*AB	A*AB	A*AB	A*AB		C-F	C-F	C-F	C-F
R6	59.00	35.99	4.74	1.51		40.21	47.94	11.34	4.64
R1	58.84	36.00	3.66	0.86		48.97	39.18	7.73	4.12
R7	58.41	35.56	5.82	0.65		37.63	47.42	11.34	3.09
R2	57.97	36.42	5.17	0.43		38.14	43.81	13.40	4.12
R4	51.51	42.46	5.39	0.43		44.85	45.36	9.79	3.61
R5	42.24	50.00	7.97	0.43		31.96	46.39	21.65	4.12
R3	34.69	54.50	10.34	0.86		22.16	61.86	15.46	4.64

*Table 5-7: Representation – Ordered easiest to challenging by A*AB group*

	Representation
R6	Understand and explain phenomena represented as a diagrams, graphs, tables or in a mathematical form
R1	Use technical and scientific language
R7	Communicate data and physics concepts as diagrams, graphs, tables, math form
R2	Work with approximation, orders of magnitude, proportion, rates, exponentials..
R4	Apply scientific method and conventions
R5	Search for and understand information about concepts.
R3	Define phenomena in relevant physics terms

Mastery of Experimental Investigation

*Table 5-8: Expt. Invest – Ordered easiest to challenging by A*AB group*

	A*AB	A*AB	A*AB	A*AB		CF	CF	CF	CF
	%Ease	%Effort	%Guid	%Chal		%Ease	%Effort	%Guid	%Chall
E6	53.66	37.28	7.76	1.08		37.11	47.42	11.34	4.64
E4	51.94	41.38	5.39	0.86		53.09	39.69	5.15	4.12
E2	39.44	48.71	10.78	0.86		29.38	55.67	15.46	3.61
E8	37.50	50.22	12.93	1.51		26.29	46.91	20.62	7.22
E5	33.62	52.59	12.72	1.08		27.32	53.61	15.98	4.64
E7	31.90	57.76	9.48	0.86		24.74	56.19	15.98	5.15
E1	28.66	63.58	6.90	0.86		26.29	56.19	17.53	4.12
E3	25.65	57.33	17.67	1.29		24.74	49.48	21.65	8.25

*Table 5-9: Expt. Invest. – Ordered easiest to challenging by A*AB group*

	Experimental Investigation – Planning, Performing and Describing Experiments
E6	Analyse and Interpret data
E4	Accurately observe and measure
E2	Determine a set of variables to control
E8	Understand the relationship between theory and experiment- i.e. design experiments from theory or apply physics theory to experiments
E5	Determine the reliability and plausibility of results
E7	Develop and refine conclusions
E1	Identify phenomenon or physical properties involved
E3	Modify and adapt standard methods and procedures to detect, identify and quantify

Mastery of Problem Solving

*Table 5-10: Problem Solving – Ordered easiest to challenging by A*AB group*

	A*AB	A*AB	A*AB	A*AB		CF	CF	CF	CF
	%Ease	%Effort	%Guid	%Chall		%Ease	%Effort	%Guid	%Chall
P3	50.40	43.75	6.00	0.65		36.08	46.39	13.92	4.12
P1	43.97	51.08	6.47	1.08		34.54	43.81	18.56	3.09
P2	41.38	46.98	10.13	1.72		32.47	40.21	19.59	8.25
P7	39.22	41.16	16.16	3.23		20.62	33.51	28.35	17.53
P9	34.05	46.55	17.89	1.94		18.56	40.72	29.90	11.34
P6	32.76	45.91	16.16	4.96		15.46	40.21	27.84	16.49
P8	28.66	55.60	15.30	0.65		19.59	48.97	26.29	5.67
P5	26.08	53.23	17.24	3.66		17.53	43.30	29.90	9.28
P4	18.97	48.28	24.35	4.53		20.10	35.57	34.02	10.31

*Table 5-11: Problem Solving – Ordered   easiest to challenging by A*AB group*

	Problem Solving
P3	Ask relevant questions, identify patterns and relationships
P1	Distil a problem to its basic elements
P2	Break down abstract and complex problems into multiple stages
P7	Apply geometrics and algebraic proofs
P9	Combine or rework equations to suit new situations and context
P6	Translate a narrative into mathematical form
P8	Explore alternative ideas or solutions to problems
P5	Explain abstract, theoretical situations or models
P4	Create new ways of framing a problem or phenomenon

Mastery of Reasoning and Thinking

*Table 5-12: Reasoning + Thinking – Ordered easiest to challenging by A*AB group*

	A*AB	A*AB	A*AB	A*AB		CF	CF	CF	CF
	%Ease	%Effort	%Guid	%Chal		%Ease	%Effort	%Guid	%Chall
T2	50.00	43.97	6.03	0.43		32.99	53.09	9.28	3.09
T3	48.00	45.26	6.25	0.65		29.38	50.52	14.43	4.12
T5	43.10	47.41	8.41	1.08		32.99	45.36	15.98	4.64

	A*AB	A*AB	A*AB	A*AB		CF	CF	CF	CF
	%Ease	%Effort	%Guid	%Chal		%Ease	%Effort	%Guid	%Chall
T1	31.90	57.76	11.21	1.51		21.13	53.09	20.62	4.12
T9	31.03	51.94	16.16	1.08		17.53	45.88	27.32	7.73
T4	30.82	55.60	13.15	0.65		23.71	53.09	19.07	3.09
T11	30.17	54.74	12.07	3.45		22.16	46.39	22.16	7.73
T7	29.09	52.16	15.52	3.23		14.43	42.78	33.51	8.25
T10	25.22	51.29	21.77	2.16		13.92	44.85	27.84	11.34
T6	24.78	50.65	21.55	3.02		19.07	45.88	25.26	8.76
T8	18.75	51.51	25.86	3.88		15.46	37.11	33.51	12.89

*Table 5-13: Reasoning + Thinking – Ordered easiest to challenging by A*AB group*

	Thinking and Reasoning
T2	Draw on prior knowledge relevant to the task or phenomenon
Y3	Interconnect prior and new knowledge
T5	Imagine the object or event in ' ideal' conditions
T1	Understand the nature of physics - axioms, theories, principles, conventions
T9	Deduce - reason from a general principle to a special case
T4	Take any statement about the individual object or event and generalise.
T11	Defend your ideas /premise by constructing logical arguments
T7	Apply known principles to complex, imagined or theoretical situations
T10	Induce - reason from a number of special cases to a general principle
T6	Apply probabilistic reasoning
T8	Develop compelling ideas and hypotheses

Mastery of Modelling

*Table 5-14: Modelling – Ordered easiest to challenging by A*AB group*

	A*AB	A*AB	A*AB	A*AB		CF	CF	CF	CF
	%Ease	%Effort	%Guid.	%Chall.		%Ease	%Effort	%Guid.	%Chall.
M5	46.98	45.69	6.47	0.65		33.51	44.33	15.46	6.19
M3	39.01	49.57	8.84	1.94		27.84	44.85	19.07	7.22
M4	32.97	57.97	8.41	0.43		22.68	55.15	17.01	4.64
M2	25.22	49.57	19.40	5.60		17.01	41.24	27.32	13.92
M9	24.14	47.63	22.84	4.96		11.34	36.60	29.90	21.13

	A*AB	A*AB	A*AB	A*AB		CF	CF	CF	CF
	%Ease	%Effort	%Guid.	%Chall.		%Ease	%Effort	%Guid.	%Chall.
M1	22.20	56.03	19.40	1.94		10.31	47.42	31.44	10.31
M6	21.77	53.45	21.34	3.23		15.98	48.45	23.20	10.82
M1	21.77	59.70	15.30	3.23		11.86	52.06	24.74	9.79
M8	20.69	43.10	29.09	7.11		11.86	28.87	34.54	24.23
M7	19.83	54.09	22.20	3.45		13.92	35.57	39.69	10.31
M10	14.66	57.33	23.06	4.53		9.79	36.60	39.18	13.40

*Table 5-15: Modelling – Ordered easiest to challenging by A*AB group*

	Modelling
M5	Use logic to deduce a relationship
M3	Visualisation of data - mentally organise and process
M4	Interpret prior learning and experience for new situations
M2	Produce a mental representation or conceptual model - thought experiments
M9	Interpret and contextualise mathematical descriptions of physical phenomena
M1	Distil complex and abstract phenomena to get to a set of parameters and relationships
M6	Come up with relevant original ideas for explaining, measuring, predicting
M11	Combine the process of evaluation and adaptation to observations, reasoning, induction, deduction modelling, prediction and testing
M8	Create a mathematical model that describes the phenomenon or problem
M7	Develop descriptive models to understand complex systems
M10	Use constituent parts to predict behaviour

Table 5-16: *Competence Ease of Mastery*

Competence	Number Indicators at Ease	Average % Frequency	Easiest Indicators / Competence
Representation	5/7	57 %	R1,R2,R4,R6
Expt. Invest.	2/8	53%	E4, E6
Prob. Solve	3/9	45%	P1, P2, P3
Think+ Reason	3/11	45%	T3, T4, T5
Modelling	3/11	40%	M3, M4, M5

Table 5-6 to Table 5-16 shows that, in the case for all Physics Competences those indicators that were mastered with greatest Ease were found to be procedural or procedural/cognitive competences, whereas the Indicators which were more challenging to master were advanced cognitive competences.

Representation had the greatest portion of Indicators that could be mastered with Ease, as shown by the highest average frequency response of all Indicators. Figure 5-7, the A*AB grade group for the Representation Competence showed the most consistency of score at Ease level with R1, R6 and R7 all scoring the highest Ease score of 59%, compared to an average score of 42% for the C-F grade group. For the higher achieving students, this higher level of Representation mastery may provide an advantage for these students across all other competences. H.A.Simon's opinion (1977), quoted by Van Heuvelen is important here.

''Finding facilitating representations for almost any class of problem should be seen as a major intellectual achievement, one that is often greatly underestimated as a significant part of both problem solving efforts in science and efforts in instructional design.

Donald Norman (2001), physicists and educationalist also stressed the importance of Representation

"The powers of cognition come from abstraction and representation: the ability to represent perceptions, experiences, and thoughts in some medium other than that in which they have occurred, abstracted away from irrelevant details. This is the essence of intelligence, for if the representation and the processes are just right, then new experiences, insights and creations can emerge".

This could be a possible argument for a focused development of the Representation competence in the evolving physicist. In addition to this distinct difference for Representation for the two grade groups, it should be noted that for each competence there were significant differences at the Ease level that were less extreme for the other scale levels. This may be some indication of sub groups among the populations which could be explored with further analysis. In any case the spread warranted further exploration and therefore a correlation analysis was carried out**.**

5.4 Physics Competence Correlation Analysis

Stage 5 is the Development of a Correlation Matrix

A correlation analysis of the indicators was produced to explore the individual indicators further. Using Excel and SPSS a 46 x 46 pairwise correlation matrix was produced. The correlation coefficients were positive for all crosswise pairs. A full distribution of the correlation coefficients matrix is shown colour coded as a two dimensional heat-map array in Figure 5-12, where the 5 competences and their corresponding indicators are set out.

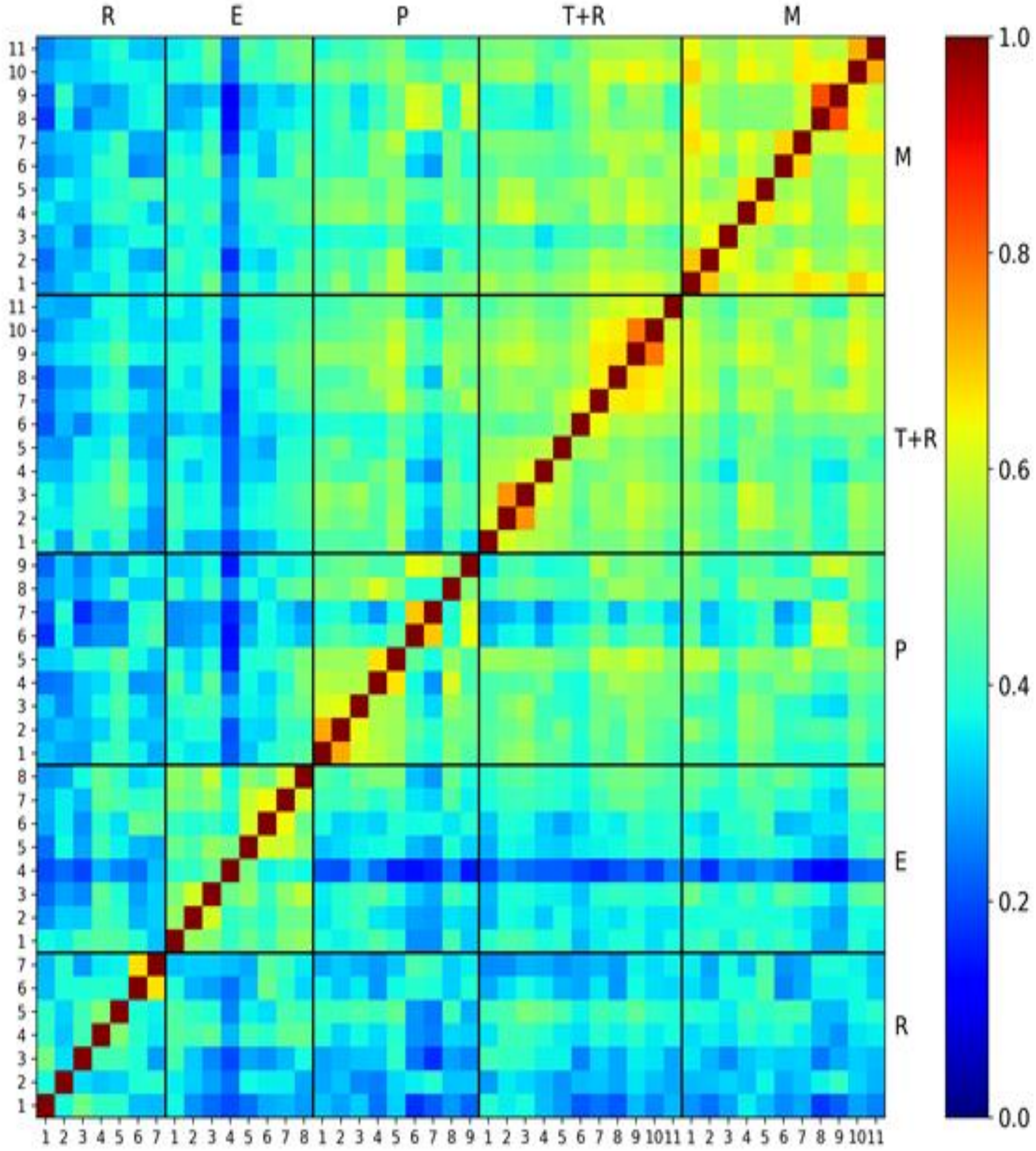


Figure 5-12: Heat Map of the Pairwise Correlation of each of the 46 Indicators

Indicators are shown as R1-7, E1-8, P1-9, T1-11, M1-11.

The Heat Map shows the following:

- There are no negatively correlated pairs, the covariance is positive for all indicators.
- The Representation R and Experimental Investigation E Competences are the most independent sets of Indicators, with the lowest level of correlation between indicators. In Representation, R4 and R5 are the most highly correlated of this set. R4 *Apply Scientific Method and Conventions* and R5 *Search for and Understand Information about Concepts.*

- The lowest correlation and consistently low correlation coefficients ranged from 0.2-0.37 occurred in Experimental Investigation. Note Indicator E4 – *Accurately Observe and Measure*. On the Ease scale for cohort C-F, Table 5-8, indicator E4, level of Ease was almost twice that of any other indicator and the highest level of Ease across all competences. It could therefore be said that E4 is the most independent, generic, procedural indicator and recognisable as a given for physics.
- Similarly, but to a lesser extent P6 and P7 Problem Solving- *Translate a narrative into mathematical form*, *Apply geometric and algebraic proofs*. (correlation coefficients 0.2-0.48), suggesting that these indicators are also independent and generic.

- M1 and M10 have the strongest correlations for the whole matrix, Table 5-17, and came out with the lowest Ease score for the C-F cohort, therefore considered the most challenging. *M1 Distil complex and abstract phenomena to get to a set of parameters and relationships. M10 Use constituent parts to predict behaviour.*

- The level of correlation between Indicators within the three competences, Problem Solving, Thinking+ Reasoning, Modelling are highest and occurs in increasing order. Such that the highest correlated Indicator pairs are within Thinking + Reasoning and Modelling.

- The level of correlation is important in showing how certain sets of indicators mark out sets of specific competences, for example related to mathematics strengths are the Indicators R6, R7, P6, P7, P9, where being able to achieve one pertains to achieving the other and vice versa.

- There is some inter-competence correlation P6, T6, T9, T10, M1, M8. These are related to mathematics and are high level cognitive competences.

- The greatest number of correlated pairs occurs in Modelling, 19 pairs, suggesting that this set of Modelling indicators are the most distinct and co-dependent set. This strong correlation among the indicators of the Modelling competence shows Modelling as the most specialised competence and most discriminating of the levels of mastery of the population. Perhaps it is mastery of these most highly correlated indicators which mark out the inherent or gifted physicist because mastery of one indicator pertains to mastery of others and vice versa.

- The highest correlations, appearing as yellow, orange and red on the heat map, have correlation coefficients of 0.60 and above.

The outliers in this correlation analysis again suggests that perhaps some of these indicators would map much better onto other competences. Therefore the use of Principle Component Analysis as a further analysis technique may be useful here for such mapping. This would mean that the Indicator sets could be changed for any of the Competences and this may aid teaching and learning, making a positive contribution to curriculum development.

Table 5-17: Correlation Coefficients: p >0.6 Pairs of Indicators per Competences

	Paired Indicators					
Corr. Coeff.	Inter - competence	Repre.	Expt. Invest.	Prob. Solve	Think+ Reason	Modelling
0.60	M1/T10: T9/P6					
0.62	M8/P6:				T9/T11:	
0.63				P2/P3:		M7/M4: M7/M2: M1/M4:
0.64			E6/E7	P6/P9	T6/T10: T7/T10:	M2/M7: M2/M3:
0.65					T7/T8: T8/T9	M1/M11:M8/M10: M7/M11
0.66					T9/T10:	M7/M10: M9/M10: M1/M8
0.67		R6/R7:		P4/P5:		M1/M7: M4/M5
0.68						M1/M10: M5/M6
0.70				P6/P7:		M1/M2
0.72						M10/M11
0.73				P1/P2:		
0.75					T2/T3	
0.78					T9/T10	
0.83						M8/M9
No of paired indicators /competence		1	1	5	8	19

5.5 Mastery of Physics Competences: Physicists and STEM Graduates.

It might be expected that physicists score on physics competences differently from other physics learners. Since 98% of respondents were STEM qualified at university level then this comparison could be representative of Physicist compared to STEM graduates. A visual inspection of Figure 5-13 and Figure 5-14 showed that there appeared to be differences and therefore a statistical test was carried out on the data to find the asymptotic significance at $p< 0.05$ and results are presented in Table 5-18. The Physicists scored higher levels of Ease and lower levels of Challenge as seen by comparing the scores for each indicators for Physicists with those for All Respondents in Table 5-18 . The percentage differences Physicists – All Respondents were calculated where All Respondents are all physics learners and includes the Physicists.

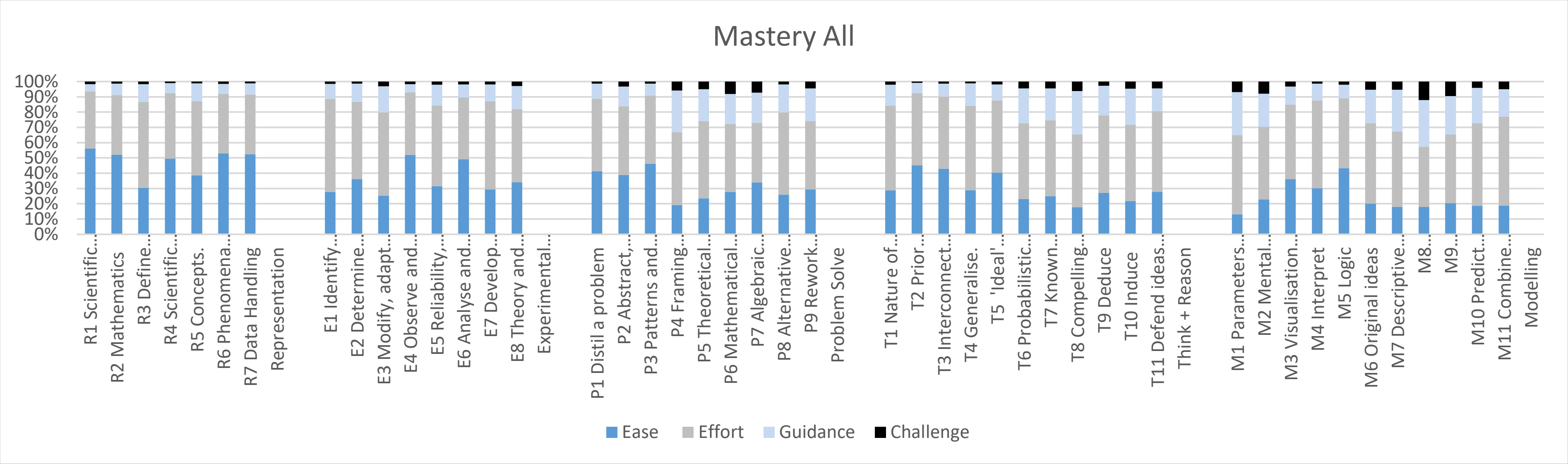


Figure 5-13: Mastery of Physics Competences for All Respondents Figure 5-14: Mastery of Physics Competences by Physicists

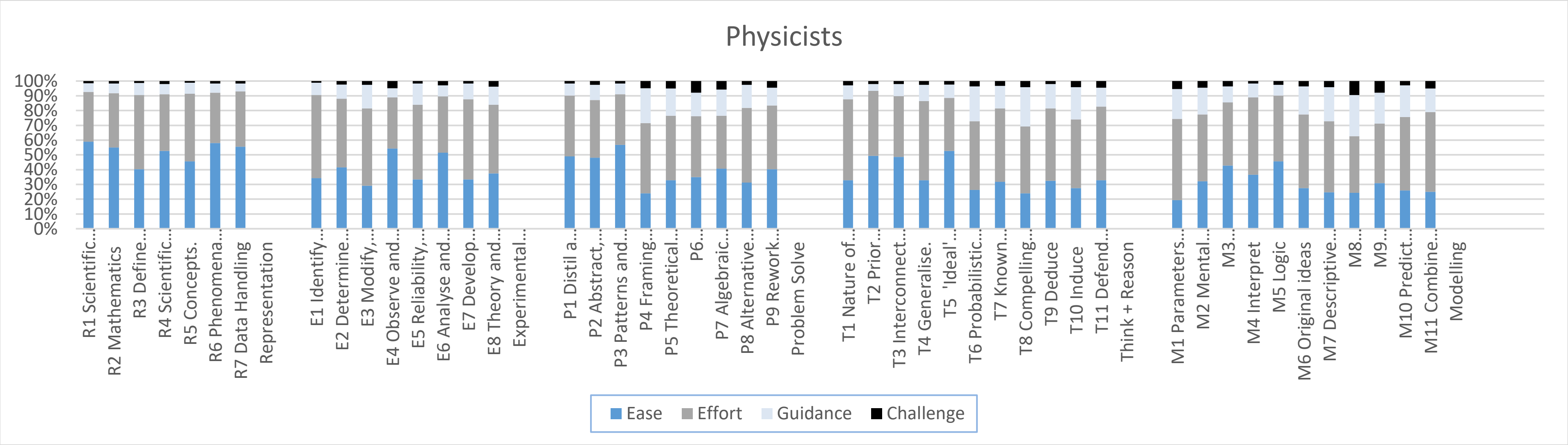


Table 5-18: Comparison of Mean Scores at Each Scale Level: All Respondents cf Physicists

Representation														
Phy.	Ease	Effort	Guid.	Chall.	All	Ease	Effort	Guid.	Chall.	Phy-All	Ease	Effort	Guid.	Chall.
R1	59.00	33.60	5.80	1.60	R1	55.0	37.4	4.70	1.70	R1	3.10	-3.80	1.10	-0.10
R2	55.20	36.80	6.70	1.30	R2	52.10	38.9	7.50	1.40	R2	3.10	-2.10	-0.80	-0.10
R3	40.40	50.20	8.20	1.20	R3	30.30	56.0	11.6	1.70	R3	10.00	-5.80	-3.40	-0.50
R4	52.80	38.60	7.30	1.30	R4	49.00	42.5	6.40	1.10	R4	3.80	-3.90	0.90	0.20
R5	45.80	45.80	7.50	0.90	R5	38.50	48.1	11.7	1.20	R5	7.30	-2.30	-4.20	-0.30
R6	58.10	34.30	6.30	1.30	R6	52.80	38.8	6.40	1.50	R6	5.30	-4.50	-0.10	-0.20
R7	55.70	37.40	5.30	1.60	R7	52.20	39.0	7.30	1.20	R7	3.50	-1.60	-2.00	0.40
Mean	52.00	39.50	6.73	1.31	Mean	42.50	38.4	7.29	1.26	DiffMean	9.91	1.09	-0.56	0.06

Experimental Investigation														
Phy.	Ease	Effort	Guid.	Chall.	All	Ease	Effort	Guid.	Chall.	Phy-All	Ease	Effort	Guid.	Chall.
E1	34.20	56.40	8.20	1.20	E1	27.50	60.40	9.70	1.50	E1	6.70	-4.00	-1.50	-0.30
E2	41.70	46.60	9.60	2.10	E2	35.90	50.10	11.70	1.40	E2	5.80	-3.50	-2.10	0.70
E3	29.20	52.30	16.00	2.50	E3	25.00	54.00	17.00	3.00	E3	4.20	-1.70	-1.00	-0.50
E4	54.30	37.40	6.20	2.10	E4	51.40	40.60	5.30	1.70	E4	2.90	-3.20	0.90	0.40
E5	33.40	50.60	14.40	1.60	E5	31.20	52.40	13.50	2.00	E5	2.20	-1.80	0.90	-0.40
E6	51.40	38.60	7.50	2.50	E6	48.70	39.90	8.50	1.80	E6	2.70	-1.30	-1.00	0.70
E7	33.30	54.30	10.80	1.60	E7	29.20	57.10	11.10	1.80	E7	4.10	-2.80	-0.30	-0.20
E8	37.40	46.50	12.40	3.70	E8	33.90	47.50	14.90	2.90	E8	3.50	-1.00	-2.50	0.80
Mean	39.36	47.84	10.64	2.16	Mean	32.43	45.48	11.46	1.86	DiffMean	6.93	2.36	-0.82	0.31

Problem Solving														
Phy.	Ease	Effort	Guid.	Chall.	All	Ease	Effort	Guid.	Chall.	Phy-All	Ease	Effort	Guid.	Chall.
P1	49.10	41.30	8.30	1.30	P1	40.90	47.20	9.70	1.40	P1	8.20	-5.90	-1.40	-0.10
P2	48.30	39.70	10.30	1.70	P2	38.50	44.70	12.60	3.30	P2	9.80	-5.00	-2.30	-1.60
P3	56.90	34.50	7.40	1.20	P3	46.00	44.30	7.80	1.40	P3	10.90	-9.80	-0.40	-0.20
P4	23.90	47.80	23.80	4.50	P4	19.10	47.30	26.90	5.90	P4	4.80	0.50	-3.10	-1.40
P5	32.90	43.90	18.90	4.30	P5	23.30	50.10	20.70	5.00	P5	9.60	-6.20	-1.80	-0.70
P6	35.40	41.20	16.40	7.00	P6	27.40	44.00	19.30	8.10	P6	8.00	-2.80	-2.90	-1.10
P7	40.80	35.90	17.80	5.50	P7	33.50	38.70	19.50	7.20	P7	7.30	-2.80	-1.70	-1.70
P8	31.20	50.20	16.50	2.10	P8	25.70	53.40	18.30	1.80	P8	5.50	-3.20	-1.80	0.30
P9	40.50	43.40	11.90	4.20	P9	29.20	44.60	21.20	4.40	P9	11.30	-1.20	-9.30	-0.20
Mean	39.89	41.99	14.59	3.53	Mean	29.40	42.80	16.30	4.02	DiffMean	10.49	-0.82	-1.71	-0.49

Thinking + Reasoning

Phy.	Ease	Effort	Guid.	Chall.	All	Ease	Effort	Guid.	Chall.	Phy-All	Ease	Effort	Guid.	Chall.
T1	32.90	54.90	9.80	2.30	T1	28.50	54.90	13.70	2.00	T1	4.40	0.00	-3.90	0.30
T2	49.90	44.70	4.60	0.80	T2	44.70	46.40	6.70	0.90	T2	5.20	-1.70	-2.10	-0.10
T3	48.90	41.50	8.40	1.20	T3	42.60	46.60	8.40	1.40	T3	6.30	-5.10	0.00	-0.20
T4	33.90	53.60	11.60	0.90	T4	28.50	54.60	14.60	1.10	T4	5.40	-1.00	-3.00	-0.20
T5	53.70	35.90	9.20	1.20	T5	39.90	46.60	10.40	1.80	T5	13.80	-10.7	-1.20	-0.60
T6	26.60	46.70	23.80	2.90	T6	22.80	49.00	22.40	4.40	T6	3.80	-2.30	1.40	-1.50
T7	32.70	49.80	15.40	2.10	T7	24.50	49.00	20.50	4.40	T7	8.20	0.80	-5.10	-2.30
T8	23.90	46.30	26.90	2.90	T8	17.50	47.00	27.90	6.20	T8	6.40	-0.70	-1.00	-3.30
T9	32.80	49.60	16.70	0.90	T9	26.80	49.90	19.20	2.70	T9	6.00	-0.30	-2.50	-1.80
T10	28.80	46.70	21.90	2.60	T10	21.60	49.20	23.30	4.60	T10	7.20	-2.50	-1.40	-2.00
T11	33.90	49.90	12.80	3.40	T11	27.50	52.10	14.80	4.40	T11	6.40	-2.20	-2.00	-1.00
Mean	36.18	47.24	14.65	1.93	Mean	31.51	49.57	16.54	3.08	DiffMean	4.67	-2.33	-1.89	-1.15

Modelling

Phy.	Ease	Effort	Guid.	Chall.	All	Ease	Effort	Guid.	Chall.	Phy-All	Ease	Effort	Guid.	Chall.
M1	19.50	55.60	20.40	4.50	M1	12.90	51.00	27.50	6.80	M1	6.60	4.60	-7.10	-2.30
M2	32.30	45.40	18.80	3.50	M2	22.50	46.90	21.50	7.80	M2	9.80	-1.50	-2.70	-4.30
M3	43.20	43.00	10.90	2.90	M3	35.50	47.90	11.60	3.20	M3	7.70	-4.90	-0.70	-0.30
M4	36.70	52.70	9.80	0.80	M4	29.70	56.90	10.70	1.40	M4	7.00	-4.20	-0.90	-0.60
M5	45.80	44.60	7.90	1.70	M5	42.80	45.10	8.80	2.00	M5	3.00	-0.50	-0.90	-0.30
M6	28.40	49.80	18.90	2.90	M6	19.80	51.80	21.60	5.20	M6	8.60	-2.00	-2.70	-2.30
M7	24.90	48.60	23.20	3.30	M7	17.80	48.40	27.10	5.20	M7	7.10	0.20	-3.90	-1.90
M8	24.60	38.60	28.20	8.60	M8	17.80	38.70	30.40	11.90	M8	6.80	-0.10	-2.20	-3.30
M9	30.90	41.30	21.20	6.60	M9	20.10	44.10	24.70	9.40	M9	10.80	-2.80	-3.50	-2.80
M10	25.90	49.90	21.80	2.40	M10	18.40	53.30	22.70	4.10	M10	7.50	-3.40	-0.90	-1.70
M11	25.90	53.90	16.40	3.80	M11	18.60	57.20	17.80	4.90	M11	7.30	-3.30	-1.40	-1.10
Mean	30.74	47.58	17.95	3.73	Mean	23.26	49.21	20.40	5.63	DiffMean	7.48	-1.63	-2.45	-1.90

Where negative numbers appear in the columns for Guidance and Challenge, this indicates that the STEM respondents sought more guidance and experienced higher levels of challenge than Physicists. For each Competence, the mean values at each scale level was calculated. Using this mean value at the Ease level for the difference between Physicists and All Respondents, those indicators which were greater than this mean difference value, were selected. This set of Indicators are given in Table 5-19 and may be considered to be the set of indicators and competences for which the Physicists were stronger than STEM graduates. With the exception of R3, *Define phenomena in relevant physics terms* these strengths are for the Problem Solving (P3, P9), Thinking + Reasoning (all except T1, T6) and Modelling (M2,3,6,9,10) and encompass the advanced cognitive competences.

Table 5-19: Indicators – Physicists higher levels of Ease cf STEM graduates

	Indicators which had higher scores for physicists
R3	Define phenomena in relevant physics terms
P3	Ask relevant questions, identify patterns and relationships
P9	Combine or rework equations to suit new situations and context
T2	Draw on prior knowledge relevant to the task or phenomenon
T3	Interconnect prior and new knowledge
T4	Take any statement about the individual object or event and generalise.
T5	Imagine the object or event in ' ideal' conditions
T7	Apply known principles to complex, imagined or theoretical situations
T8	Develop compelling ideas and hypotheses
T9	Deduce - reason from a general principle to a special case
T10	Induce - reason from a number of special cases to a general principle
T11	Defend your ideas /premise by constructing logical arguments
M2	Produce a mental representation or conceptual model - thought experiments
M3	Visualisation of data - mentally organise and process
M6	Come up with relevant original ideas for explaining, measuring, predicting
M9	Interpret and contextualise mathematical descriptions of physical phenomena
M10	Use constituent parts to predict behaviour

5.6 Mastery of Physics Competences: Gender Differences between Physicists

Table 5-20 shows the Ease percentage responses for female and male physicists. Marking out those where males score higher than females and vice versa, shows that the males more often reported that they could do the advanced cognitive competences with Ease. Females exceeded males in the greater choice for the procedural competences, most notably in Experimental Investigation. Remembering that the female physicists match the academic achievements of the male physicists at every qualification level in higher education, the gendered difference here is that of self-assessment and description of academic self.

Table 5-20: Comparison Percentage Frequencies for Male and Females

	Representations	**%M**	**%F**	**%M -%F**
R1	Use technical and scientific language	61	51	>
R2	Work with approximation, orders of magnitude, proportion, rates, exponentials etc.	55	49	>
R3	Define phenomena in relevant physics terms	34	25	>
R4	Apply scientific method and conventions	49	48	>
R5	Search for and understand information about concepts.	39	37	>
R6	Understand and explain phenomena represented as a diagrams, graphs, tables or in a mathematical form	54	51	>
R7	Communicate data and physics concepts as diagrams, graphs, tables or in a mathematical form	52	53	<
	Experimental Investigation			
E1	Identify phenomenon or physical properties involved	33	23	>
E2	Determine a set of variables to control	32	39	<
E3	Modify and adapt standard methods and procedures to detect, identify and quantify	23	27	<
E4	Accurately observe and measure	46	57	<
E5	Determine the reliability and plausibility of results	34	29	>
E6	Analyse and Interpret data	46	50	<
E7	Develop and refine conclusions	28	31	<
E8	Understand the relationship between theory and experiment- i.e. design experiments from theory or apply physics theory to experiments	35	32	>
	Problem Solving			
P1	Distil a problem to its basic elements	43	38	>
P2	Break down abstract and complex problems into multiple stages	41	36	>
P3	Ask relevant questions, identify patterns and relationships	46	45	>
P4	Create new ways of framing a problem or phenomenon	22	16	>
P5	Explain abstract, theoretical situations or models	29	17	>
P6	Translate a narrative into mathematical form	25	30	<
P7	Apply geometrics and algebraic proofs	34	33	<
P8	Explore alternative ideas or solutions to problems	29	22	>
P9	Combine or rework equations to suit new situations and context	26	31	<

	Thinking and Reasoning	%Male	%Female	
T1	Understand the nature of physics - its axioms, theories, principles and conventions	35	22	>
T2	Draw on prior knowledge relevant to the task or phenomenon	48	41	>
T3	Interconnect prior and new knowledge	45	40	>
T4	Take any statement about the individual object or event and generalise.	30	26	>
T5	Imagine the object or event in ' ideal' conditions	48	32	>
T6	Apply probabilistic reasoning	25	19	>
T7	Apply known principles to complex, imagined or theoretical situations	27	21	>
T8	Develop compelling ideas and hypotheses	26	14	>
T9	Deduce - reason from a general principle to a special case	27	26	>
T10	Induce - reason from a number of special cases to a general principle	24	19	>
T11	Defend your ideas /premise with logical arguments	49	56	<
	Modelling			
M1	Distil complex and abstract phenomena to get to a set of parameters and relationships	16	12	>
M2	Produce a mental representation or conceptual model - thought experiments	29	15	>
M3	Visualisation of data - mentally organise and process	35	36	<
M4	Interpret prior learning and experience for new situations	30	29	>
M5	Use logic to deduce a relationship	41	44	<
M6	Come up with relevant original ideas for explaining, measuring, predicting	23	12	>
M7	Develop descriptive models to understand complex systems	20	16	>
M8	Create a mathematical model that describes the phenomenon or problem	21	25	<
M9	Interpret and contextualise mathematical descriptions of physical phenomena	21	19	>
M10	Use constituent parts to predict behaviour	20	16	>
M11	Combine the process of evaluation and adaptation to observations, reasoning, induction, deduction modelling, prediction and testing	20	16	>

5.7 Development of Mastery Scale

The four point ordinal scale of mastery was developed further using data handling techniques to create a continuous numerical scale of range 1- 4. The purpose of such a scale is to demonstrate the range of mastery which can be considered to be success in physics and by which a student could assess their capacity for doing physics.

In the preceding analysis of responses to all 46 Indicators on the four point ordinal scale, the metrics produced confirmed correlation with the academic attainment levels of the respondents . Although an ordinal scale is limited by the fact that it cannot be treated as scale data, accepting this limitation, but to investigate the scale further by a statistical analysis of the levels, Ease, Effort, Guidance and Challenge were replaced with the markers 1-4 respectively. This was not to impose any linearity on the scale but solely to accommodate further mathematical handling of the data. Therefore for each Indicator any given response was 1-4 respectively. Summing the sets of Indicator responses, a mean value could be calculated for each respondent. In this way for each competence, if any respondent replied to all indicators with an Ease score then the mean value for any given competence would be 1. If a respondent most frequently chose Ease but sometimes Guidance or Challenge – the mean would be greater than 1 etc. And so the mean for any such respondent could vary $1 < m < 4$. In this way a set of 657 mean values were created for each competence. Summing and taking the average for each competence, ranked the competences from least to most difficult to master as Representation, Experimental Investigation, Thinking + Reasoning, Problem Solving and Modelling, corresponding to the ranking on Section 5.2 and Section 5.4. Although in this analysis Problem solving and Thinking + Reasoning are not distinctly different, see Table 5-21 and indeed all the means are within the standard deviation of each other.

Table 5-21: Mean Scores per Competence and Standard Deviation.

	Representation	Expt. Invest.	Prob. Solve	Think+ Reason	Modelling
Mean	1.56	1.72	1.86	1.83	1.98
Std dev.	0.40	0.45	0.52	0.52	0.32

This process produced a set of mean values and by correcting to 1 decimal place, the means could be binned at intervals of 0.1 units, thus producing the mean scores per competence for the whole population as shown in Figure 5-15, Figure 5-16, Figure 5-17, Figure 5-18, Figure 5-19.

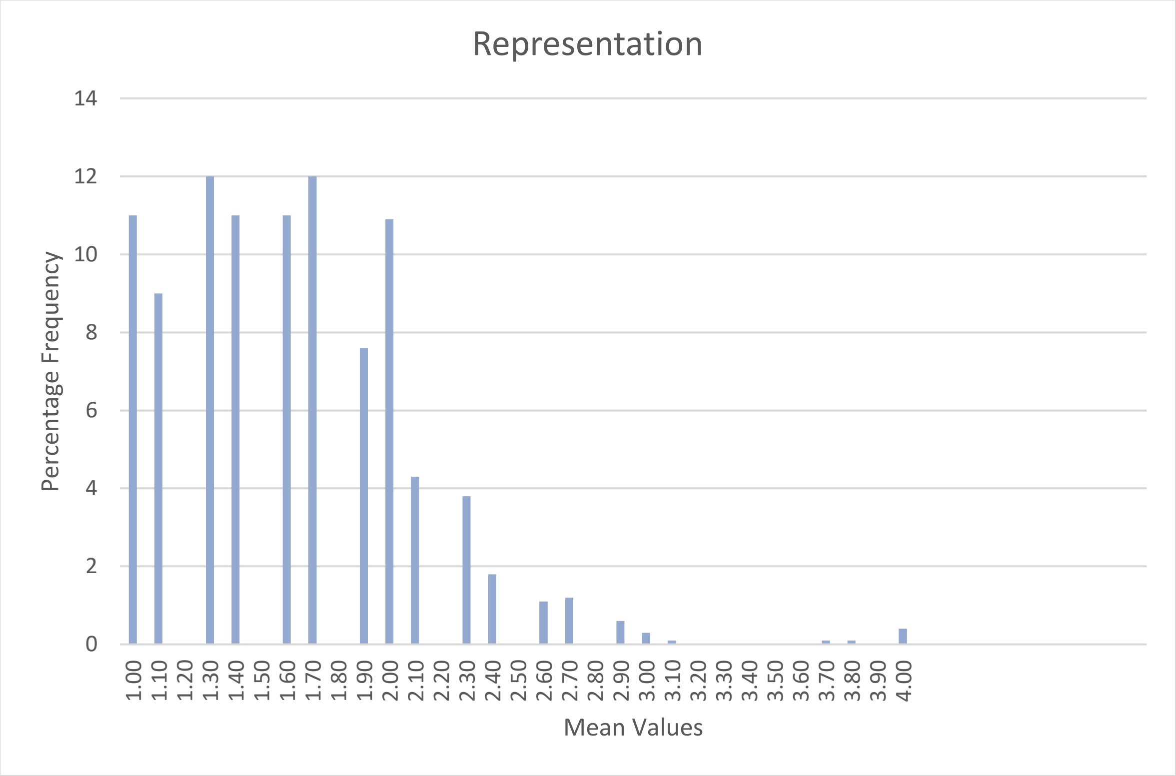


Figure 5-15: Frequency of Mean Values for the Representation Competence

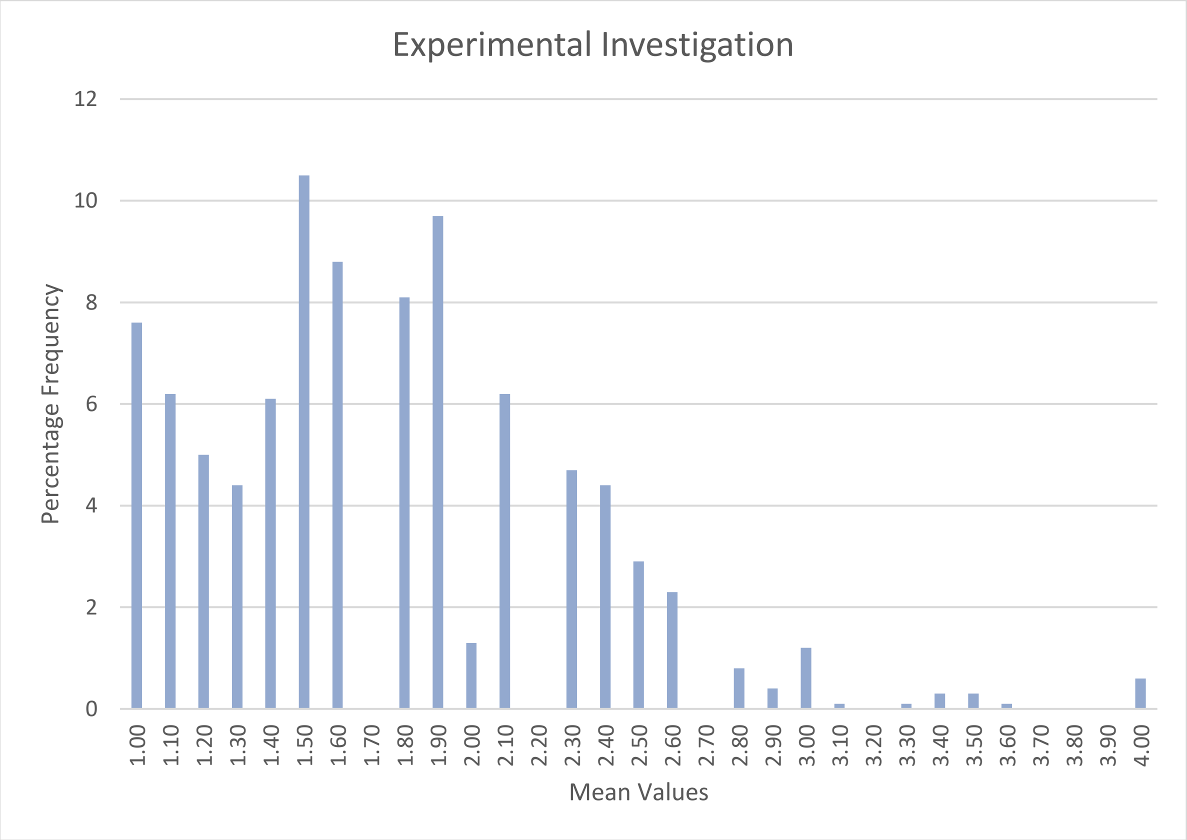


Figure 5-16: Frequency of Mean Values for the Expt. Invest. Competence

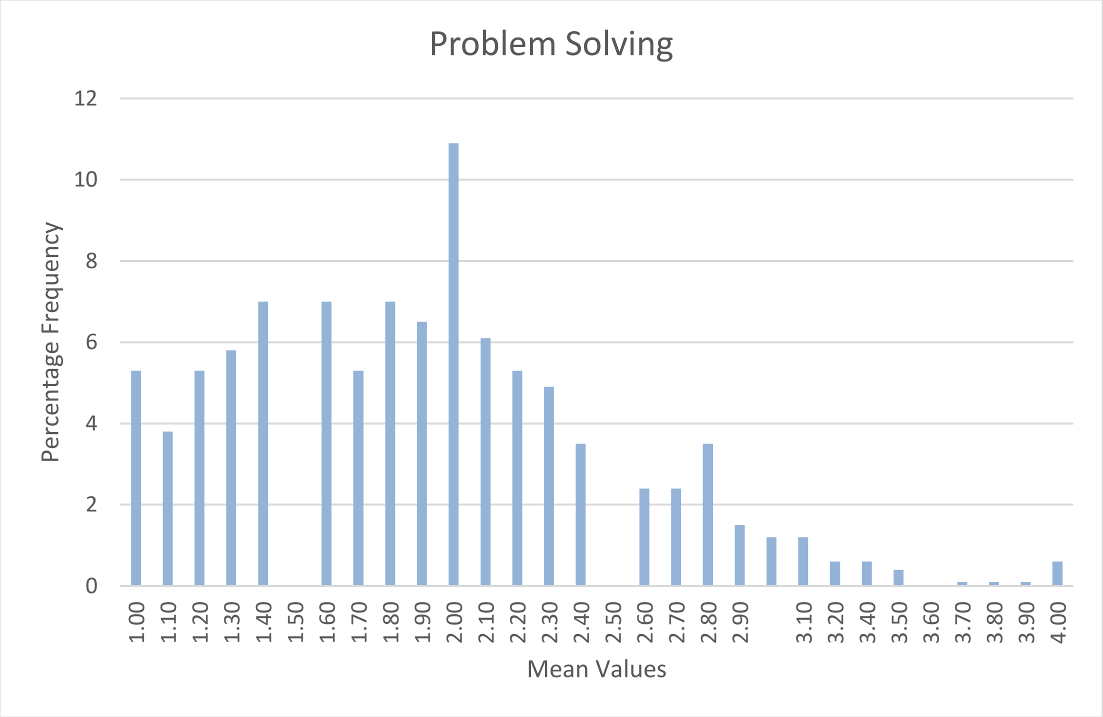


Figure 5-17: Frequency of Mean Values for the Problem Solving Competence

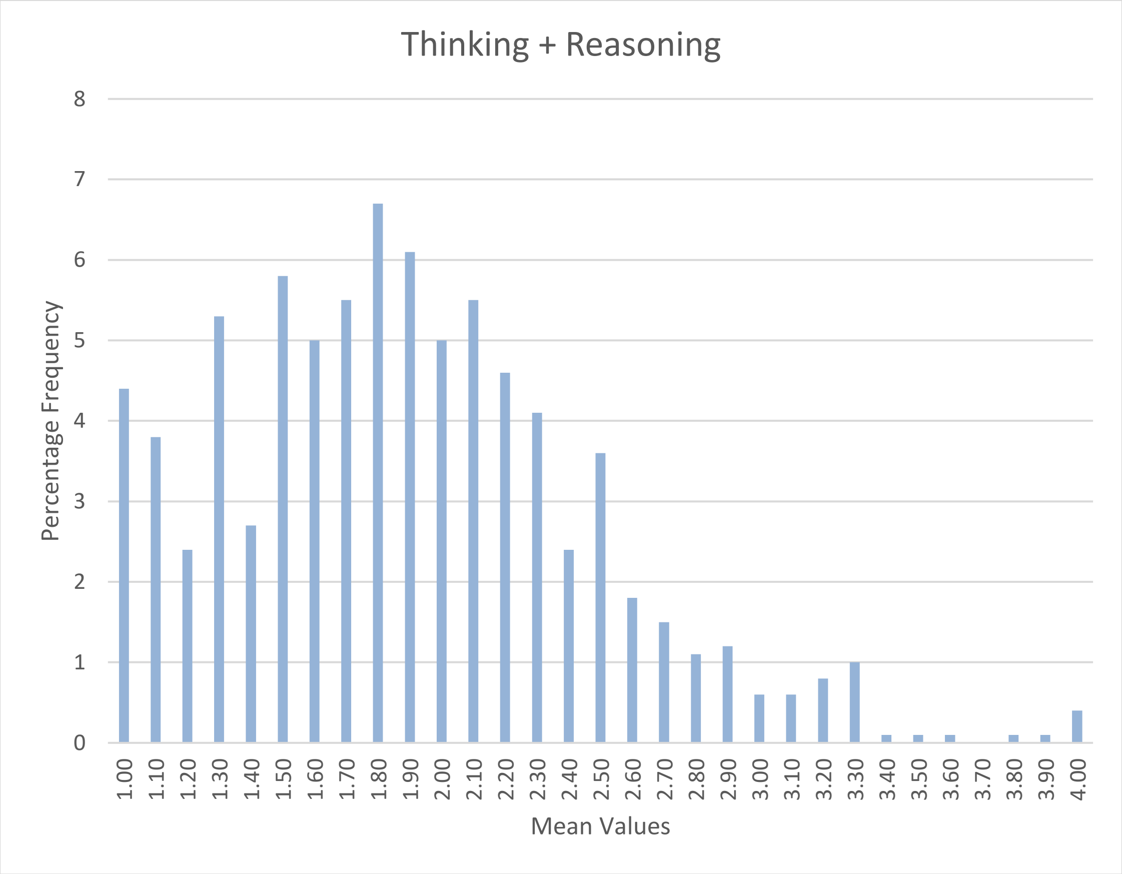


Figure 5-18: Frequency of Mean Values for the Thinking+ Reasoning Competence

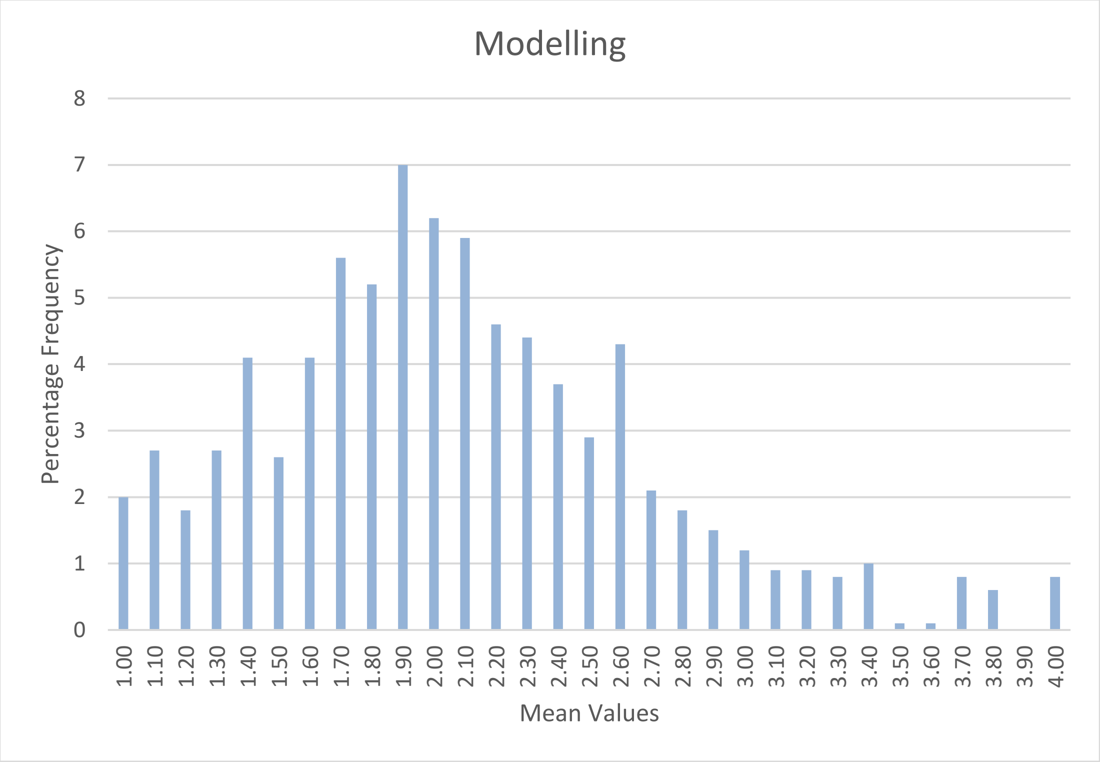


Figure 5-19: *Frequency of Mean Values for the Modelling Competence*

Examination of these Figures concludes with the features:

- A statistical approach developed the 4 point scale towards a continuous scale and so the non-linearity of the four point scale gains discrimination.
- The Representation and Experimental Investigation Competences show fewer points on the scale within the bell distribution envelope. These are procedural competences mastered with relative ease when compared to the other Competences
- Progression from Representation to Experimental Investigation, Problem Solving, Thinking + Reasoning and Modelling shows the evolving two tailed distribution.
- The number of mean values created for each competence increases as Rep 16, Expt. Invest 24, Prob. Solve 27, Think+ Reason 30, Modelling 30 respectively. The increased number of mean values are a measure of the greater discrimination on the scale and the greater spread in levels of mastery typical in a population of physics learners for these cognitive competences.

5.8 Calibration of Mastery Scale

To produce a calibrated scale of mastery for all five Physics Competences a master graph was produced by calculating average values for all 46 indicators. This produced a bell shaped distribution of frequencies as shown in Figure 5-20.

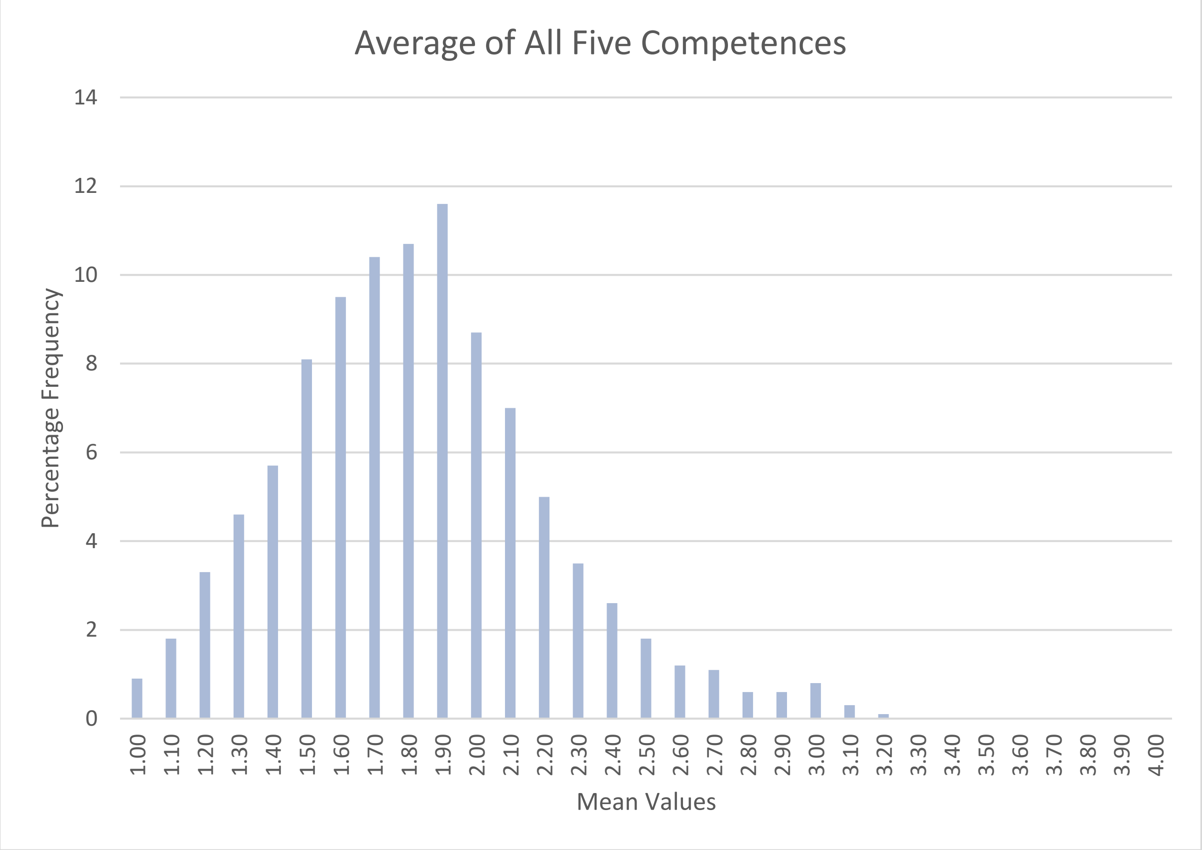


Figure 5-20: Cumulative Mean Scores for all Five Competences.

This is the calibrated Response Scale for the target population, that is for a population of predominantly high achieving STEM professionals of which 48.7% had A level physics grades in the A*A, B band. Therefore, using this scale, any candidate could be assessed for their capacity for mastery of Physics Competences by completing the questions Q13-Q17 (although the language may need to be adjusted for the relevant target population, e.g. A level students) and comparing their mean score to this calibrated chart. So rather than a fixed threshold to physics success there is a spectrum. Wherever the candidate appears on the scale, they could feel encouraged to study physics because the scale is that of those who have succeeded in physics. By corollary the response scale could be used to target appropriate support or curriculum and pedagogy development for certain physics competence levels. In addition any other response scale could be calibrated for a different population and therefore the appropriate scale for a given population could be used in physics assessments, for example undergraduates or potential A Level students.

5.9 Summary – Physics Competences

An analysis using Excel and SPSS showed that varying degrees of mastery were measured for the five competences and the 46 indicators within. Hence it could be discerned that the Competences and Indicators could be ranked for levels of challenge.

The analysis of the average frequency data showed a one tail bell shaped distribution, for which the tail related to the more challenging aspects of doing physics. It would be expected that a two tail distribution would occur if a less highly physics educated and high ability group had responded.

The four point scale of Ease, Effort, Guidance and Challenge discriminated between two groups of different academic attainment at A Level. Those with grades A*A,B compared to the grade C-F group. Frequency data analysis for each group ranked the indicators according to challenge and therefore provides a good guide for improvement in pedagogy, directing where support would be needed for success with certain procedural and cognitive competences. In both grade groups, the procedural and procedural/cognitive competences are more often mastered with ease.

A correlation analysis showed where Indicators were most correlated. The Competences were mainly independent with few significant cross correlations. Representation and Experimental Investigation Indicators being most independent or generic whereas Problem Solving, Thinking and Reasoning and Modelling encompassed the most highly correlated Indicator sets.

Modelling was shown as the most challenging with the highest degree of correlation between its indicators. Therefore any level of mastery of one indicator pertains to a similar level of mastery with the correlated indicators. With the corollary that if an indicator cannot be mastered others would also be too challenging to master.

Coding the mastery scale levels, Ease, Effort, Guidance and Challenge to values of 1 – 4 allowed a mean value for all competences to be created for all respondents. This confirmed the ranking of the Physics Competences in range of difficulty to master, in the order Representation, Experimental Investigation, Problem Solving, Thinking + Reasoning and Modelling .

Taking the 657 unique mean values of total mastery of the five Physics Competences, binned to 0.1 intervals, produced a range of 1-3.1. Plotting a frequency distribution of these means, created a continuous scale of mastery. This scale is a response scale for a high achieving population of mostly STEM educated respondents who were successful in Physics A level, and their subsequent higher education and career.

Use of the scale adapted to suit another population at a different academic level could allow potential physics candidates to see where they would lie within the range of mastery of a group of successful physics learners and so could be encouraged to continue to study physics. More encouraging than a fixed threshold entry.

Chapter 6 : Results and Discussion – Learning Profile

This chapter presents and discusses results relating to Research Question 2: *How do those who have studied physics 'post 16' self-identify their profile of Cognitive and Procedural Competences, Learning Competences and Learning Characteristics in physics? Are there Demographic Differences?*

Question 12 in the questionnaire was designed to encompass Research Question 2 and therefore to collect all aspects that may be considered to impact on the study of physics. This catch-all question had 69 indicators. Respondents were asked to choose all indicators which, with the benefit of hindsight, they considered best described their physics-student-self at A level. Collectively the responses to these 69 indicators for all respondents was considered to produce a 'Physics Learning Profile'. The need for identifying such a profile is supported by the research literature, discussed in Section 2.4. It explained that isolated pedagogic changes do not show any maintained, improved understanding in physics nor bring about any increase in the numbers of students opting to study physics. Rather Crowley, Van Heuvelan and others have identified that a network or web model would be required. Barron and Crowley refers to a *'learning ecology' (Hecht, Knutson and Crowley 2019; Van Heuvelen 1991; Barron 2006).*

6.1 Physics Learning Profile

Based on this paradigm, a Physics Learning Profile was produced from a descriptive analysis of the data. Taking the total number of respondents as 657, percentage responses for each of the 69 indicators were calculated to produce the Learning Profile as shown in Figure 6-1 and Figure 6-2.

To accommodate the Learning Profile on the page and legibly, it has been divided into two graphs. Those Indicators which were chosen by more than 45% of respondents and those chosen less than 45%. See Figure 6-1 and Figure 6-2 . These two graphs give the reader an overview of the Learning Profile before further analysis.

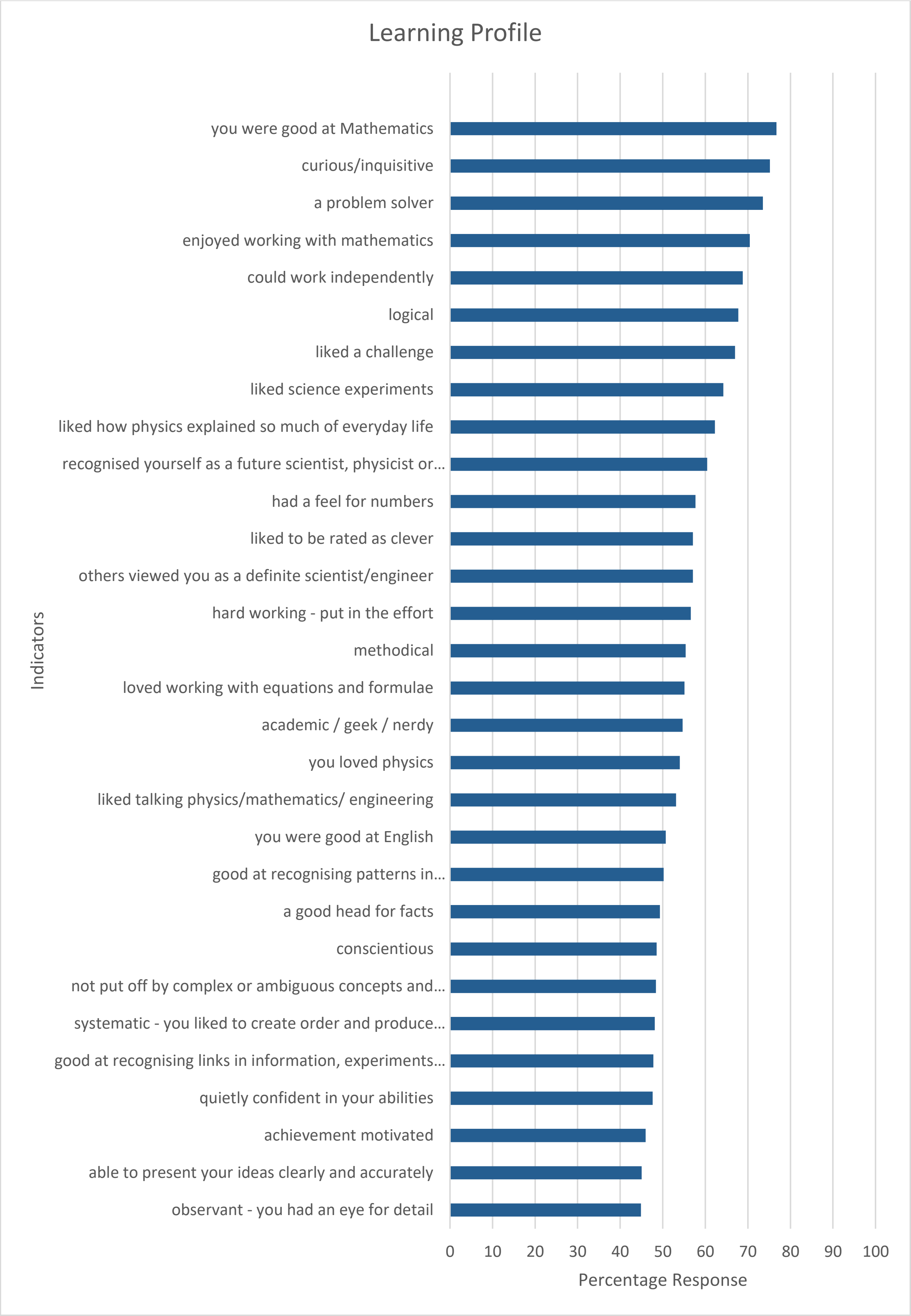


Figure 6-1:Learning Profile – Indicators chosen by more than 45% of respondents

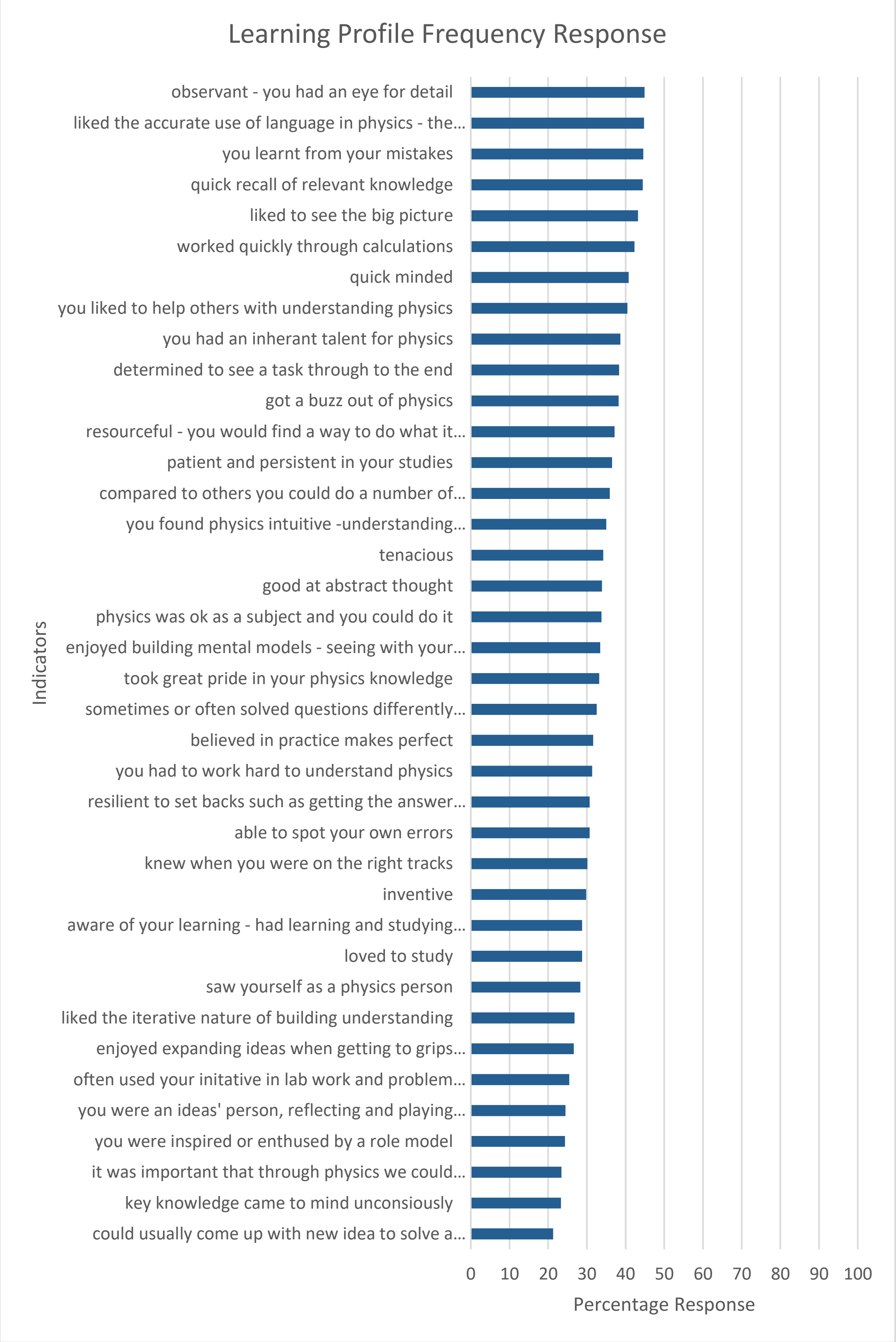


Figure 6-2: Learning Profile – Indicators chosen by less than 45% of respondents

6.2 Analysis of the Learning Profile

From this point forward the indicators of Q12 have been assigned an alpha-numeric code as set out in Appendix C. These are used to identify the Indicators in all tables and figures. It is of note that out of the 657 respondents 98.6% were educated to graduate level and above and of the remaining 1.4%, 66% were HND level. Of the graduate level respondents 98.2% were STEM graduates. Therefore it was important to examine the data through this STEM lens. Accordingly the data was explored for those who had completed degrees in the categories of Physics, Chemistry, Biology, Mathematics, Engineering, Computer Science, Geography/Geology and Non-STEM subjects, where each of these categories is detailed in Table 4-8. For example Biology includes those with degrees in the Life Sciences, Pharmacology, Microbiology, Biochemistry, Cell Biology etc.

From this point forward these subject categories are used in discussion of results, and so respondents are referred to as Physicists, Chemists, Biologists etc. or collectively as All Respondents as physics learners.

For breakdown for each STEM subject the percentage responses are calculated according to the number of respondents per category as follows. Physicists 243, Engineers 205, Biologists/ Life Sciences 53, Chemists 60, Mathematicians 31, Computing Scientists 30 and Geographers + non- STEM 35.

An overview of the data points were plotted on the following two graphs; Physicists compared to STEM graduates, Figure 6-3 and Physicists compared to non-STEM graduates, Figure 6-4. The Indicators were rearranged from questionnaire order according to the frequency scores for Physicists, and ordered most to least frequent. Visual inspection of the two graphs shows the magnitude of response for each indicator and a comparison with the Physicist response. Bearing in mind the different group sizes in each category; the very low numbers in the non-STEM group would contribute to the data spread and hence the two graphs cannot be directly compared. Note: On these graphs that the horizontal axis numbers refer to the descending order of data points and not the Indicator reference number and therefore to identify the Indicator number each data point needs to be highlighted in the electronic version of the thesis.

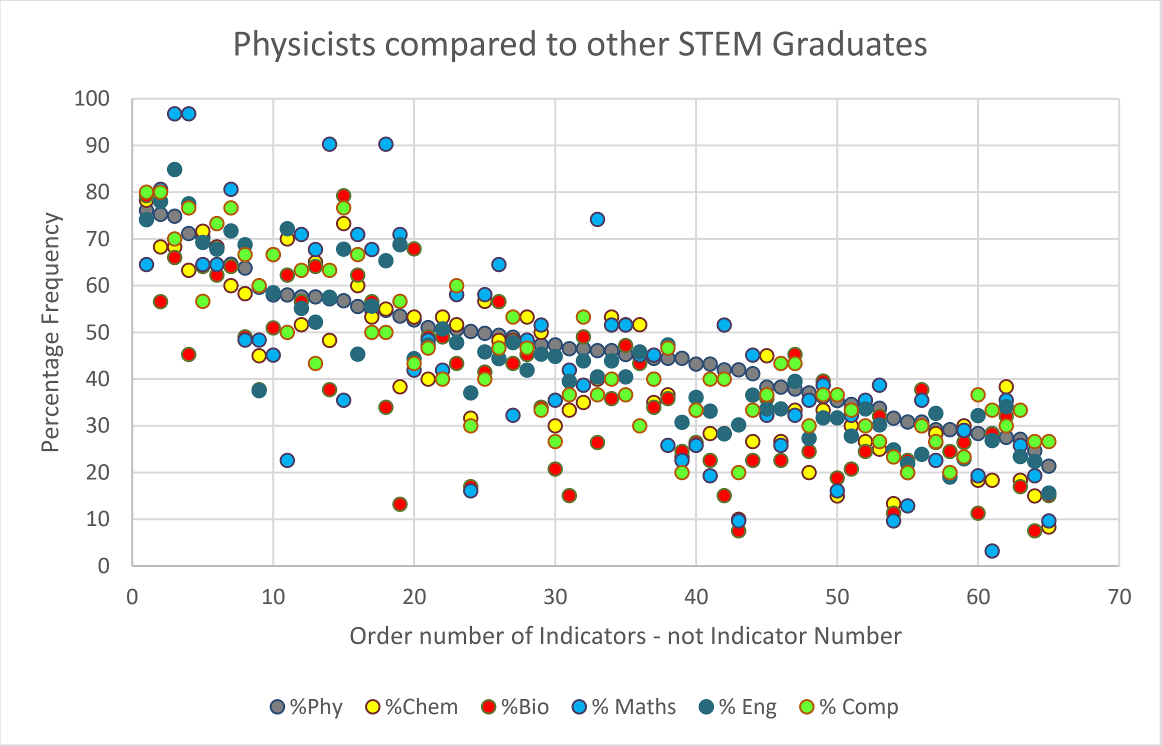


Figure 6-3: Learning Profile – All STEM Graduates compared to Physicists

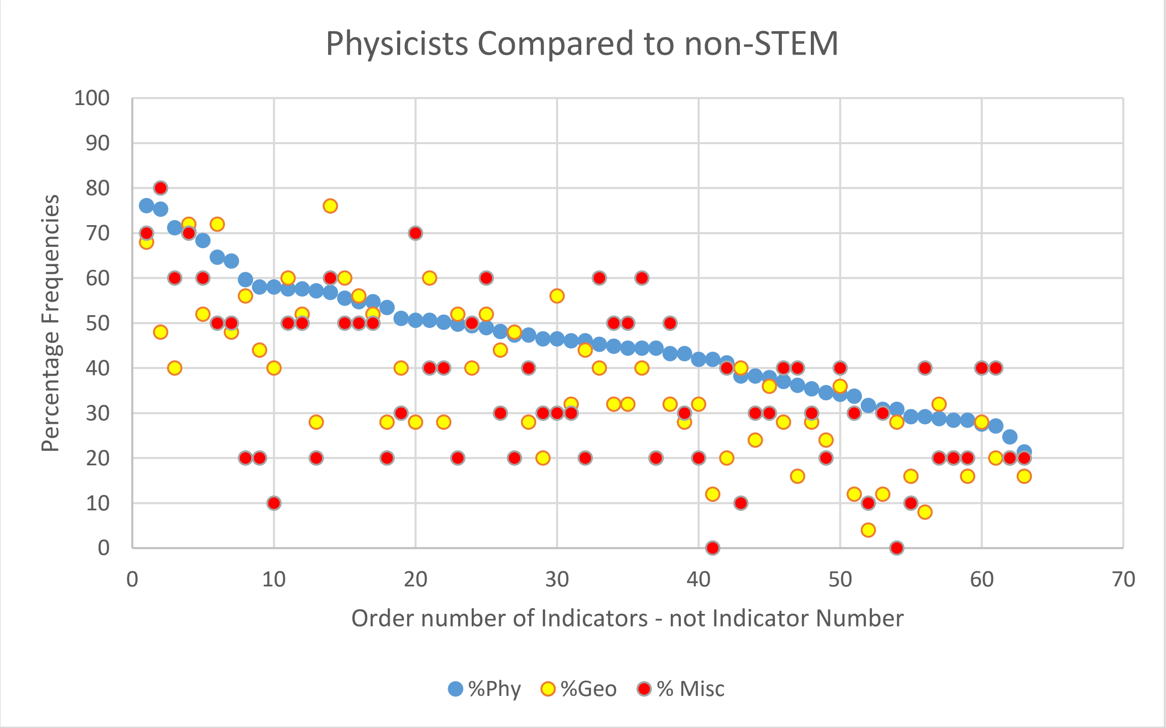


Figure 6-4: Learning Profile – Non-STEM Graduates compared to Physicists

6.2.1 Comparison of Ability and Interest in Physics

Out of the 69 indicators of Q12 there are six Indicators which related to measures of ability and interest in physics and as such differed from the other Indicators which described Physics Identity, Learning Characteristics and Competences. The six were separated out for comparison by the subject categories as defined in *Table 4-8*:

- Ability in English and Mathematics
- Level of interest/liking for physics – 3 broad categories
- If respondents felt that they had to work hard to understand physics

Table 6-1: Comparison of Ability and Interest Indicators

% Phy	% Chem	% Bio	% Maths	% Eng	% Comp	% Geo	% Non-STEM	Q12 statement
243	60	53	31	205	30	25	10	Number per group
74.9	68.3	66.0	96.8	84.9	70.0	60.0	60.0	Good at Mathematics
52.7	53.3	67.9	41.9	44.4	43.3	48.0	80.0	Good at English
66.7	41.7	30.2	29.0	54.2	63.3	32.0	50.0	Loved physics
26.8	45.0	49.1	58.1	30.7	30.0	44.0	30.0	Physics was ok as a subject
1.7	10.0	9.4	0.0	3.4	6.7	8.0	0.0	Didn't like physics but needed it
29.2	33.3	39.6	29.0	31.2	30.0	36.0	30.0	Worked hard to understand physics

Salient features of this dataset:
Of Physicists, 67% said that they 'loved physics'.

Mathematics ability among respondents was high, 60-85% of respondents in all categories and 97% among Mathematicians. By contrast high ability in English was reported by 42-53% in the groups except for the Biologists at 68% and the non-STEM group at 80% (small sample size 10)

Irrespective of the final subject at degree level, of all respondents, including physicists, approximately 30% in each category, found that they had to work hard to understand physics. Note that the indicator statement was 'you had to work hard to understand physics' rather than the subjective and 'loaded' statement 'you found physics difficult'. Considering that the set of respondents are all graduate level educated, it could be said that they belong to a band of higher intellectual ability, yet ~30% of each category acknowledge this challenge of working hard to understand physics. Perhaps their aptitude to sustain the challenge is an important learning character to possess, encourage or train in the physics student. Therefore reporting the challenge should be in a positive sense, rather than equating this challenge as 'difficulty'.

To be challenged and persevere to succeed at some level brings with it new learning and a sense of achievement, therefore reinforcing a Physics Identity that facilitates further learning.

A possible message from this set of statistics therefore may be that challenge should be celebrated as process towards deep learning rather than interpreted as difficulty.

6.2.2 Analysis Lenses

The remaining 63 Indicators encompassed the Constructs and Competences: Physics Identity, High Performance Learning Characteristics and Learning Competences

Subsequent investigation of the Learning Profile with respect to these components was through different lenses and therefore percentage figures were calculated by the group size for each lens category. For example the gender study Section 6.3.2.1, used the number of respondents who gave their gender as female or male (there was an option for respondents describe themselves as ‘other’ or not to define any gender term). That was 97 % of all respondents in the ratio 333:302 respectively.

In this way the Learning Profile was examined through the following lenses:

- Learning Profile of Physicists
- Differences in the profile by Gender
- Comparison of the Learning Profile of Physicists compared to the other STEM and non-STEM cohorts

Results for each lens on the Learning Profile were categorised into the components :

- Physics Identity
- Learning Characteristics
- Learning Competences

6.3 How Physicists Differ from Other STEM Respondents

Examining the Learning Profile for the 63 Indicators, the percentage frequency responses were calculated as explained above and are plotted/listed against Indicator number in the following graphs and tables. That is the place number on each Indicator as it appears in Question 12 of the questionnaire is assigned a reference e.g. Q12_3 and set out with the Q12 statements in Appendix C.

For the 98% of respondents who were STEM graduates, the indicator statements that had over 50% responses were selected. This gave 18 Indicators statements. These STEM responses have been sorted into the three components shown in Table 6-2 such that a typical STEM student would be recognised as follows.

Physics/STEM Identity

- Might be described as academic, geek or nerd, hardworking, conscientious, an aspiring scientist or engineer.
- Would be absorbed by STEM, enjoying talking about STEM,
- Would like to be rated as clever.

Learning Characteristics

- Curious, inquisitive.
- Methodical, could work independently,
- Hardworking-put in the effort
- Like a challenge

Cognitive Competences

- Strong mathematics ability and interest with a feel for numbers and confidence to work with equations and formulae.
- Recognising patterns in information/numbers/observations etc. showed interest in experimental work and using physics to explain much of everyday life.
- They have logical thinking ability, like to be challenged cognitively and consider themselves to be a capable problem solver.

Table 6-2: Comparison of Learning Characteristics and Competences: Physicists and STEM Qualified.

Q12 statements	%Phy.	% Av STEM	Physics Identity, Learning Characteristics and Competences
			Physics/ STEM Identity
Q12_19	55.56	61.05	academic / geek / nerdy
Q12_6	58.02	57.59	others viewed you as a definite scientist/engineer
Q12_20	58.02	55.41	recognised yourself as a future scientist, physicist or engineer
Q12_28	57.61	59.54	liked to be rated as clever
Q12_54	53.50	49.59	liked talking physics/mathematics/ engineering
			Learning Characteristics
Q12_24	75.31	72.73	a problem solver
Q12_7	76.13	75.25	curious/inquisitive
Q12_8	68.31	67.25	liked a challenge
Q12_31	70.37	65.25	could work independently
Q12_63	57.61	58.48	hard working - put in the effort
Q12_25	54.73	56.66	methodical
Q12_11	49.38	52.10	conscientious

Q12 statements	%Phy	% Av STEM	Physics Identity, Learning Characteristics and Competences
Q12_33	71.19	71.92	enjoyed working with mathematics
Q12_43	64.61	70.63	logical
Q12_48	57.20	59.46	loved working with equations and formulae
Q12_14	56.79	66.51	liked science experiments
Q12_52	54.73	58.93	had a feel for numbers
Q12_61	50.62	52.19	good at recognising patterns in information/numbers/observations etc.

Comparison for these greater than 50% frequency responses, for Physicists to all STEM graduates (comparing column 2 with column 3) confirms that Physicists are no different from the average STEM respondent for these indicators at $p< 0.05$. Table 6-2.
To find if there were Indicators for which these two groups were different, all 63 Indicator statements were examined again. Taking those which scored greater by 5% or more for the Physicists, above the average score for the STEM respondents, were considered as a significant difference. This produced the list in Table 6-3. Note that this list includes scores less than 50%, the highest score is 51% and the lowest 21%.

Table 6-3: Differences – Physicists to other STEM Respondents

Q12	%Phy.	Av STEM	Av +5%	Indicator
				Physics Identity
Q12_32	51.0	46.3	48.6	Quietly confident in your abilities
Q12_49	50.2	26.4	27.7	Got a buzz out of physics
Q12_65	47.3	31.6	33.1	You liked to help others with understanding Physics
Q12_05	46.5	33.3	35.0	You had an inherent talent for physics
Q12_47	44.4	24.2	25.5	Took great pride in your physics knowledge
Q12_18	41.9	15.5	16.3	Saw yourself as a physics person
				Motivation
Q12_50	31.7	16.5	17.3	It was important that through physics we could make the world a better place
Q12_10	30.9	19.5	20.5	You were inspired or enthused by a role model

				Learning characteristics
Q12.41	43.2	31.00	32.6	Resourceful - you would find a way to do what it takes - can do attitude
Q12_37	33.7	30.5	32.1	Resilient to set backs such as getting the answer wrong
Q12_40	21.4	15.1	15.8	Enterprising - thinking differently, striving to improve
				Learning competences
Q12_64	43.2	28.0	30.1	You found physics intuitive -understanding
Q12_27	37.0	27.5	28.8	Able to spot your own errors
Q12_56	34.6	28.8	30.3	Knew when you were on the right tracks
Q12_66	29.2	20.6	21.6	Key knowledge came to mind unconsciously
Q12_59	28.8	26.3	27.7	Enjoyed expanding ideas when getting to grips with a new topic
Q12_42	27.2	23.5	24.8	An ideas' person, reflecting and playing with ideas
Q12_58	24.7	18.2	19.1	Could usually come up with new idea to solve a problem

As before, sorting the Indicator statements into the categories Physics Identity, Learning Character and Learning Competences. Physicists differ from other STEM graduates in that Physicists more often describe their student self as follows:

Physics Identity

- quietly confident in their abilities
- got a buzz out of physics
- liked to help others with understanding physics
- had an inherent talent for physics
- took great pride in their physics knowledge
- saw themselves as a physics person

Learning Characteristics

- resourceful - would find a way to do what it takes - can do attitude
- resilient to set backs such as getting the answer wrong
- enterprising - thinking differently and striving to improve

Learning Competences

- found physics intuitive -understanding phenomena came with ease
- able to spot own errors
- knew when they were on the right tracks
- key knowledge came to mind unconsciously
- enjoyed expanding ideas when getting to grips with a new topic
- were an ideas' person, reflecting and playing with ideas
- could usually come up with new idea to solve a problem

In addition the Physicists differed in having greater levels of physics related
Motivation

- it was important that through physics the world could be made a better place
- inspired or enthused by a role model

6.3.1 Physicist Compared to Physics Learner Profiles

In an attempt to compare the physicist to each of the specific STEM graduates was only possible for engineers as the other STEM group members were too few in number. 243 Physicists, 205 Engineers, 60 Chemists, 53 Biologists, 31 Mathematicians, 30 Computer Scientists.

However as a general observation, consistently the number of Indicators chosen by physicists to describe themselves as physics learners was greater than other STEM respondents . Table 6-4 shows for 64 indicators (excluded are: Good at Mathematics or English and 3 statements referencing depth of interest in physics) the ratios of the number of Indicators chosen more often by Physicists versus other STEM respondents. Note that the mathematicians and computer scientists were closest to the physicists in their response patterns while the chemists, engineers and biologists chose ever fewer Indicators .

Table 6-4: Ratio of Frequency Indicator Choice per STEM Subject

Number of Indicators Chosen - Ratio Physicist : other STEM Respondents	
Mathematicians	36:28
Computer Scientists	37:27
Chemists	43:21
Engineers	46:18
Biologists	51:13

6.3.2 Physicists vs Engineers

Figure ***6-5*** and Table 6-5, show the difference in responses between Physicists and Engineers. As with all other analysis, the Physicists are scoring the indicators relating to physics identity and physics competences more often than the Engineers. A summary of the significant differences $p < 0.05$ is shown in Table 6-5. Results show that there were 14 indicators with a significant difference in the ratio 10:4 Physicists : Engineers. Besides the expected stronger physics identity, the Physicists more often described themselves with stronger cognitive competences than the Engineers.

Figure ***6-5*** is shown in condensed format to relay the overall form but not all Indicators are labelled on the y axis in this compressed form. Where Engineers gave a higher response is shown as negative numbers.

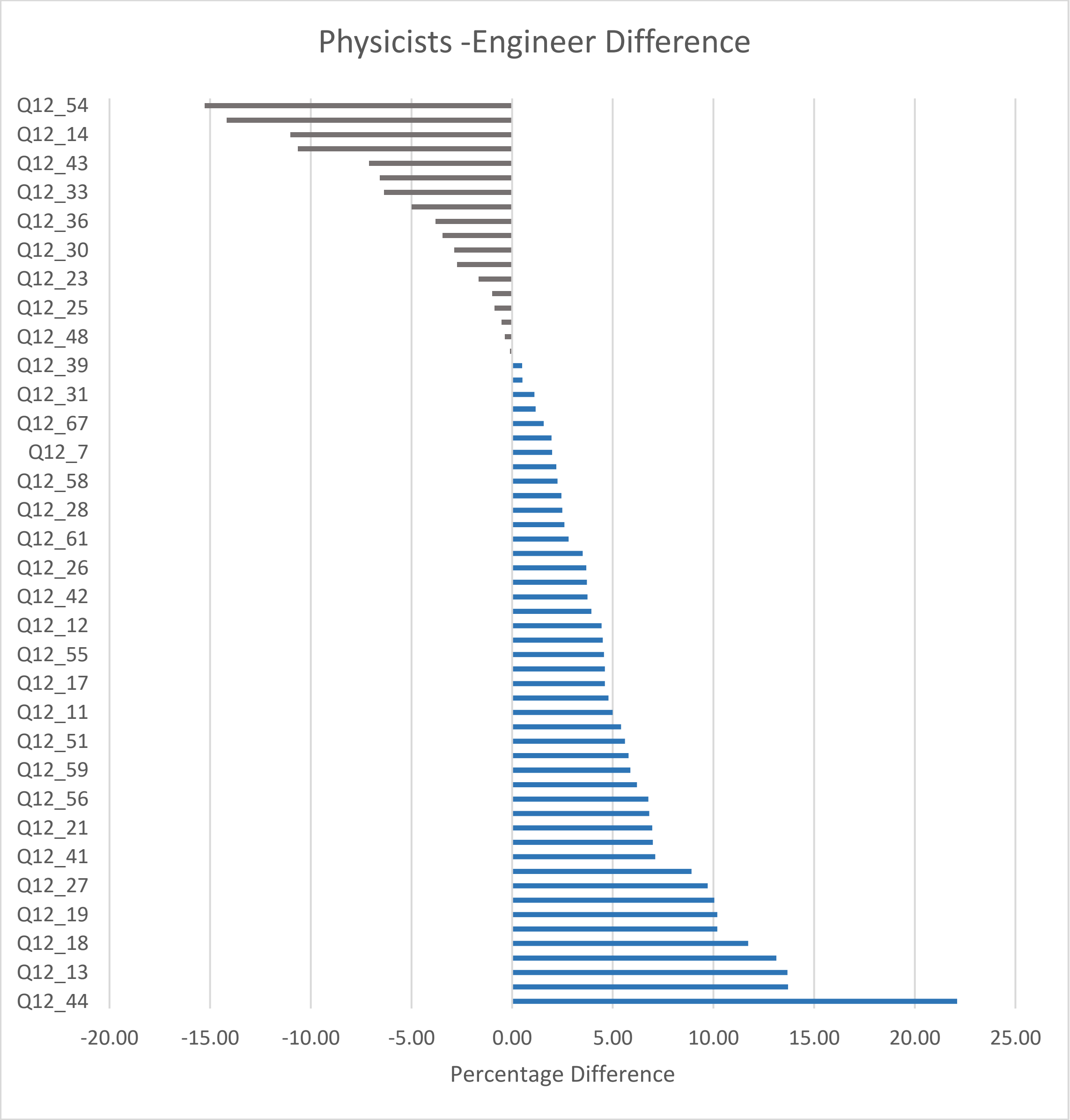


Figure 6-5: Learning Profile – Physicists compared to Engineers

Table 6-5: Learning Profile – Physicists Compared to Engineers

Q12	Phys > Eng	%Phy	% Eng	Diff	p
44	Not put off by complex or ambiguous concepts and questions	59.67	37.56	22.11	0.00
47	Took great pride in your physics knowledge	44.44	30.73	13.71	0.00
27	Able to spot your own errors	37.04	27.32	9.72	0.00
13	Good at abstract thought	41.98	28.29	13.68	0.00
49	Got a buzz out of physics	50.21	37.07	13.13	0.00
68	You were good at Mathematics	74.90	84.88	10.20	0.01
66	Key knowledge came to mind unconsciously	29.22	19.02	10.19	0.02
18	Saw yourself as a physics person	41.98	30.24	11.73	0.02
64	You found physics intuitive -understanding phenomena came with ease	43.21	33.17	10.04	0.02
10	Were inspired or enthused by a role model	30.86	21.95	8.91	0.04
19	Academic / geek / nerdy	55.56	45.37	10.19	0.04

	Eng > Phys	Phy	Eng	Diff	p
54	Liked talking physics/mathematics/ engineering	53.50	68.78	-15.28	0.00
20	Recognised yourself as a future scientist, physicist or engineer	58.02	72.20	-14.17	0.00
14	Liked science experiments	56.79	67.80	-11.01	0.02
52	Had a feel for numbers	54.73	65.37	-10.63	0.03

6.3.2.1 Gender Related Differences

Since females make up only 21% of those who study physics at A level and beyond, it was important to compare the Learning Profiles of male and female physicists. This comparison was made with 51.7% of respondents as female and therefore both males and females have an equal voice. As shown in Figure 4-5 on higher level education status, female and male respondents were equally well qualified at each level from HND up to PhD. At A-level, both male and female physicists were high achievers with over 55% achieving grade A, however in spite of this parity in academic achievement the males more often describe themselves with a stronger Physics Identity and Advanced Cognitive Performance Indicators than females. See Table 6-6 where the data is ordered by decreasing magnitude of difference between males and females.

Some examples of stronger male physics identity are in the terms: inventive, logical, good at abstract thought, whereas the females describe themselves more often in terms of their learning strategies such as self-regulation and diligence, as seen in Table 6-6 Also note as shown in Figure 6-6, that males chose more descriptors than females (female higher responses appear as negative numbers).

Comparison for the female-only STEM group (of All Respondents) showed the same outcome Figure 6-7, Table 6-6 compared to Table 6-7. So this difference between male and female self-assessments was not a feature of those who chose to become Physicists alone but applied to all female STEM respondents.

A chi squared statistical analysis for the null hypothesis, H_o that there is no difference in level of response between male and female respondents, determined that there was a significant difference between male and female responses ($p< 0.05$) for 20 of the 69 indicators among Physicists and for 41 of the 69 Indicators for All Respondents.

This is an important finding on how STEM and in particular physics should be presented in a way that takes into account the differences in identity markers of female and male students. Currently in resources promoting the study of physics and careers thereafter, the traditional physics descriptors of the qualities needed for physics are akin to those characteristics most often chosen by males and not the characteristics most often chosen by females, in this study. The finding here is that these learning characteristics; learning and self-regulation strategies that are important to female students as a way of defining their abilities and interest, should be taken as a way to encourage girls that physics is for them. Where young female students are demonstrating ability equal to the male students by grades, it must be stressed that they do have the ability and also the academic prowess required for successful physics study and achievement, even though they do not express this as their male counterparts do.

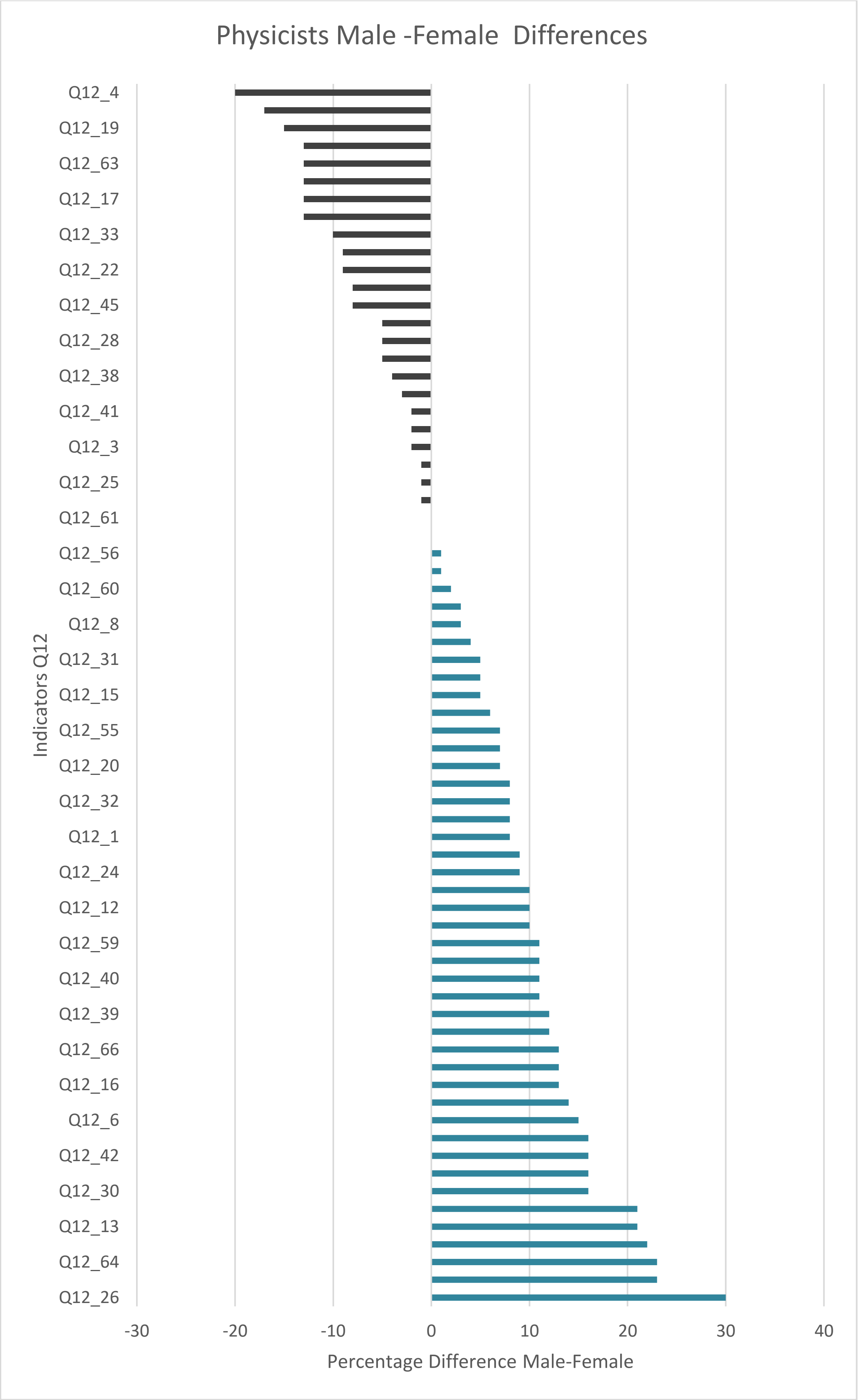


Figure 6-6: Learning Profile – Comparison Male to Female Difference – Physicists

Table 6-6: Comparison of Male and Female Choice of Descriptors – Physicists

	Male > Female for Physicists	Phy M	Phy F	Phy M-F	P
Q12_26	Inventive	51	21	30	0.00
Q12_35	Enjoyed building mental models - seeing with your mind's eye	49	26	23	0.00
Q12_64	You found physics intuitive -understanding phenomena with ease	54	31	23	0.00
Q12_46	You learnt from your mistakes	56	34	22	0.01
Q12_13	Good at abstract thought	53	32	21	0.00
Q12_54	Liked talking physics/mathematics/ engineering	65	44	21	0.05
Q12_42	You were an ideas' person, reflecting and playing with ideas	35	19	16	0.00
Q12_37	Resilient to set backs such as getting the answer wrong	41	25	16	0.01
Q12_30	Liked to see the big picture	52	36	16	0.02
Q12_58	Could usually come up with new idea to solve a problem	32	16	16	0.01
Q12_6	Others viewed you as a definite scientist/engineer	67	52	15	0.02
Q12_49	Got a buzz out of physics	56	42	14	0.04
Q12_43	Logical	71	58	13	0.03
Q12_7	Curious/inquisitive	82	70	12	0.01
Q12_40	Enterprising - thinking differently and striving to improve	27	16	11	0.02
Q12_14	Liked science experiments	63	52	11	0.00

	Female > Male for Physicists	Phy M	Phy F	Phy M-F	P
Q12_17	Patient and persistent in your studies	32	45	-13	0.00
Q12_21	Loved to study	24	37	-13	0.01
Q12_19	Academic / geek / nerdy	46	61	-15	0.01
Q12_68	You were good at Mathematics	68	81	-13	0.04
Q12_63	Hard working - put in the effort	53	66	-13	0.01

	No significant difference M>F Arranged Highest to Lowest frequency score for Physicists	Phy M	Phy F	M-F	P
Q12_66	Key knowledge came to mind unconsciously	34	21	13	0.08
Q12_16	Quick recall of relevant knowledge	52	39	13	0.08
Q12_39	Solved questions differently to others - innovative	40	28	12	0.06
Q12_53	Liked how physics explained everyday life	70	59	11	0.09
Q12_59	Enjoyed expanding ideas when getting to grips with a new topic	35	24	11	0.11
Q12_44	Not put off by complex or ambiguous concepts and questions	63	53	10	0.11
Q12_5	You had an inherent talent for physics	51	41	10	0.13
Q12_12	Quick minded	51	41	10	0.08
Q12_65	Liked to help others with understanding physics	52	43	9	0.25
Q12_24	A problem solver	80	71	9	0.14
Q12_47	Took great pride in your physics knowledge	48	40	8	0.17
Q12_27	Able to spot your own errors	40	32	8	0.30
Q12_1	You loved physics	69	61	8	0.18
Q12_32	Quietly confident in your abilities	53	45	8	0.29
Q12_55	Compared to others you could do a number of stages of a problem in your head	46	39	7	0.41
Q12_36	Liked iterative nature of building understanding	34	27	7	0.40
Q12_20	Recognised yourself as a future scientist, physicist or engineer	61	54	7	0.45
Q12_67	Used initiative in lab work and problem solving	29	23	6	0.25
Q12_18	Saw yourself as a physics person	41	36	5	0.35
Q12_15	A good head for facts	52	47	5	0.60
Q12_62	Observant - you had an eye for detail	48	44	4	0.94
Q12_8	Liked a challenge	68	65	3	0.51
Q12_57	Liked the accurate use of language in physics - the scientific terms and formulae	47	44	3	0.83
Q12_60	Good at recognising links in information, experiments and data	49	47	2	0.53
Q12_52	Had a feel for numbers	55	54	1	0.84
Q12_56	Knew when you were on the right tracks	35	34	1	0.95
Q12_61	Good at recognising patterns in information/numbers/observations etc.	51	51	0	0.90

Cont.	No Significant Difference F>M Highest to Lowest Frequency Scores	Phy M	Phy F	M-F	P
Q12_69	You were good at English	42	59	-17	0.08
Q12_11	Conscientious	42	55	-13	0.06
Q12_3	Enjoyed working with mathematics	66	76	-10	0.06
Q12_29	Systematic - you liked to create order and produce diagrams, tables etc.	44	53	-9	0.11
Q12_22	Aware of your learning - had learning and studying strategies	24	33	-9	0.11
Q12_45	Achievement motivated	44	52	-8	0.28
Q12_51	Worked quickly through calculations	40	48	-8	0.47
Q12_28	Liked to be rated as clever	54	59	-5	0.27
Q12_48	Loved working with equations and formulae	54	59	-5	0.48
Q12_23	Determined to see a task through to the end	35	40	-5	0.33
Q12_38	Believed in practice makes perfect	26	30	-4	0.13
Q12_50	It was important that through physics we could make the world a better place	30	33	-3	0.70
Q12_41	Resourceful - you would find a way to do what it takes - can do attitude	40	42	-2	0.89
Q12_9	Tenacious	35	37	-2	0.85
Q12_25	Methodical	55	56	-1	0.33
Q12_34	Able to present ideas clearly and accurately	47	48	-1	0.83
Q12_10	Inspired or enthused by a role model	29	30	-1	0.99

Comparing the gendered differences in responses for Physicists compared to gendered differences for all other respondents Figure 6-7 and Table 6-7, the overall trend was the same except that this female physicist group showed significant difference for four more learning strategies and learning characteristics indicators, affirming more strongly the female choice in these features. These four extra Indicators were: loved working with equations and formulae; had a feel for numbers; had learning and studying strategies and conscientious

For males the differences between the two male groups – male Physicists compared to all other males - were that male Physicists described themselves as : ideas people who liked reflecting on and playing with ideas, logical, they learnt by their mistakes and were resilient to set backs such as getting questions wrong. Whereas other males chose more frequently than male Physicists : that they liked the iterative nature of building up understanding, they solved problems different to others, they had an inherent talent for physics and were quietly confident in they ability.

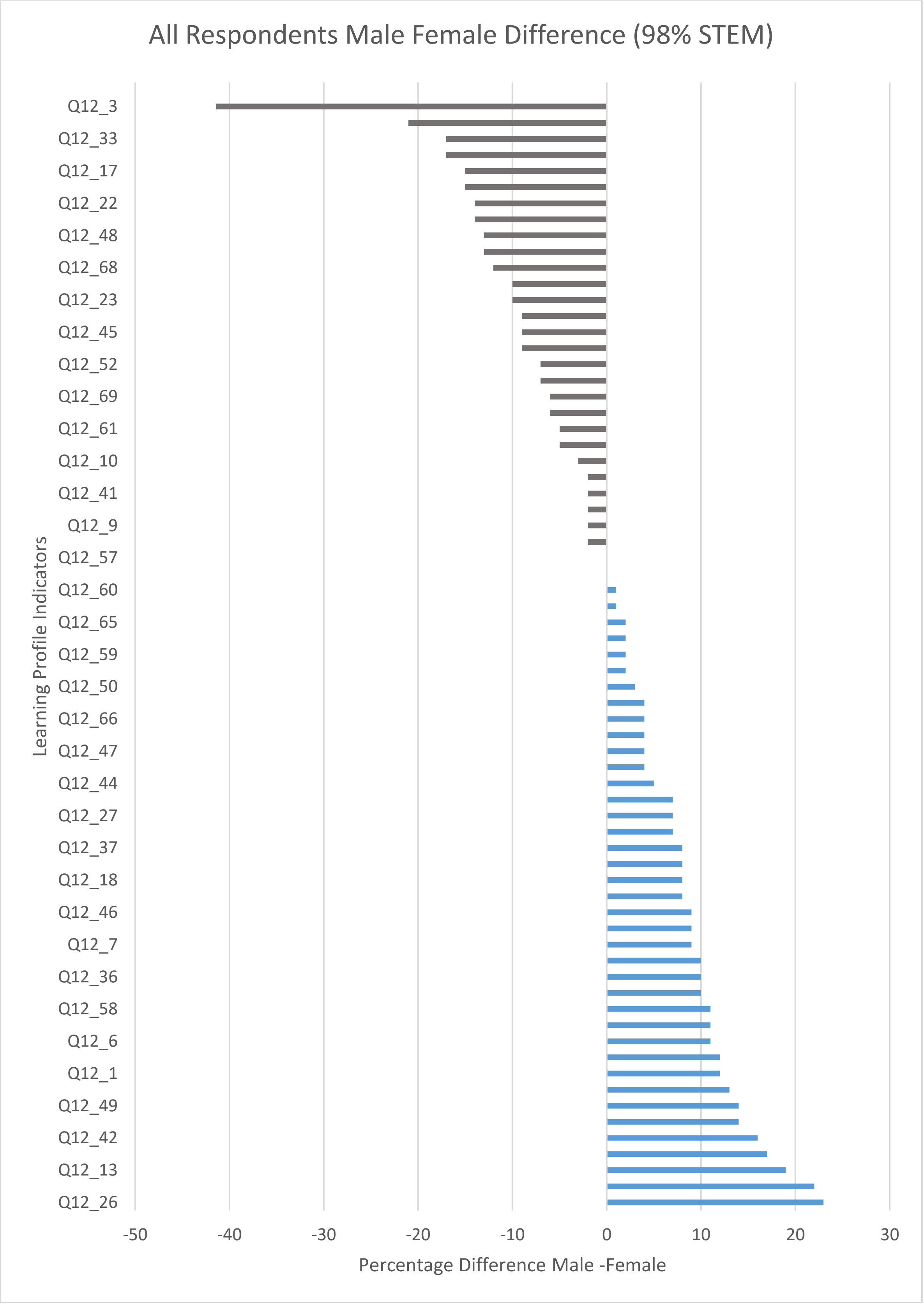


Figure 6-7: Learning Profile – Comparison Male to Female – All Respondents

Table 6-7: Learning Profile – Comparison Male to Female – All Respondents

	All Males greater significant difference to all Females	All M	All F	All M-All f	Chi M-F
Q12_26	Inventive	42	19	23	0.000
Q12_35	Enjoyed building mental models - seeing with your mind's eye	45	23	22	0.000
Q12_13	Good at abstract thought	44	25	19	0.000
Q12_54	Liked talking physics/mathematics/ engineering	62	45	17	0.000
Q12_42	You were an ideas' person, reflecting and playing with ideas	33	17	16	0.000
Q12_49	Got a buzz out of physics	45	31	14	0.001
Q12_64	You found physics intuitive -understanding phenomena came with ease	42	29	13	0.001
Q12_30	Liked to see the big picture	50	36	14	0.002
Q12_5	You had an inherent talent for physics	44	32	12	0.02
Q12_1	You loved physics	60	48	12	0.022
Q12_6	Others viewed you as a definite scientist/engineer	63	52	11	0.026
Q12_32	Quietly confident in your abilities	53	42	11	0.054
Q12_36	Liked the iterative nature of building understanding	32	22	10	0.011
Q12_39	Sometimes or often solved questions differently to others - innovative	38	28	10	0.011
Q12_7	Curious/inquisitive	80	71	9	0.012
Q12_40	Enterprising - thinking differently and striving to improve	22	13	9	0.009

Table 6-8: Learning Profile – Comparison Female to Male – All Respondents

	All females greater significant difference to all males	All M	All F	All M-All f	Chi M-F
Q12_63	Hard working - put in the effort	46	67	-21	0.00
Q12_33	Enjoyed working with mathematics	61	78	-17	0.00
Q12_21	Loved to study	20	37	-17	0,00
Q12_17	Patient and persistent in your studies	29	44	-15	0.00
Q12_4	You had to work hard to understand physics	24	39	-15	0.00
Q12_22	Aware of your learning - had learning and studying strategies	21	35	-14	0.00
Q12_11	Conscientious	41	55	-14	0.00
Q12_48	Loved working with equations and formulae	49	62	-13	0.01
Q12_19	Academic / geek / nerdy	48	61	-13	0.01
Q12_68	You were good at Mathematics	70	82	-12	0.01
Q12_52	Had a feel for numbers	54	61	-7	0.03

6.4 Age and Examination Related Differences

Differences in the responses from Physicist according to age was important to explore. Respondents who were over 46 years of age would have studied in the O. Level examination system and younger respondents would have studied the GCSE course with the inherent differences. Percentage frequency responses for all indicators showed that the GCSE cohort responded at greater frequency levels compared to the older O level physicists, showing that they had chosen more indicators to describe themselves. Differences in percentages were calculated, and significance levels of p<0.05 are shown in Table 6-9. Figure 6-8 shows the compressed profile. Negative numbers denote where the O level group chose Indicators at a greater percentage frequency than the GCSE group.

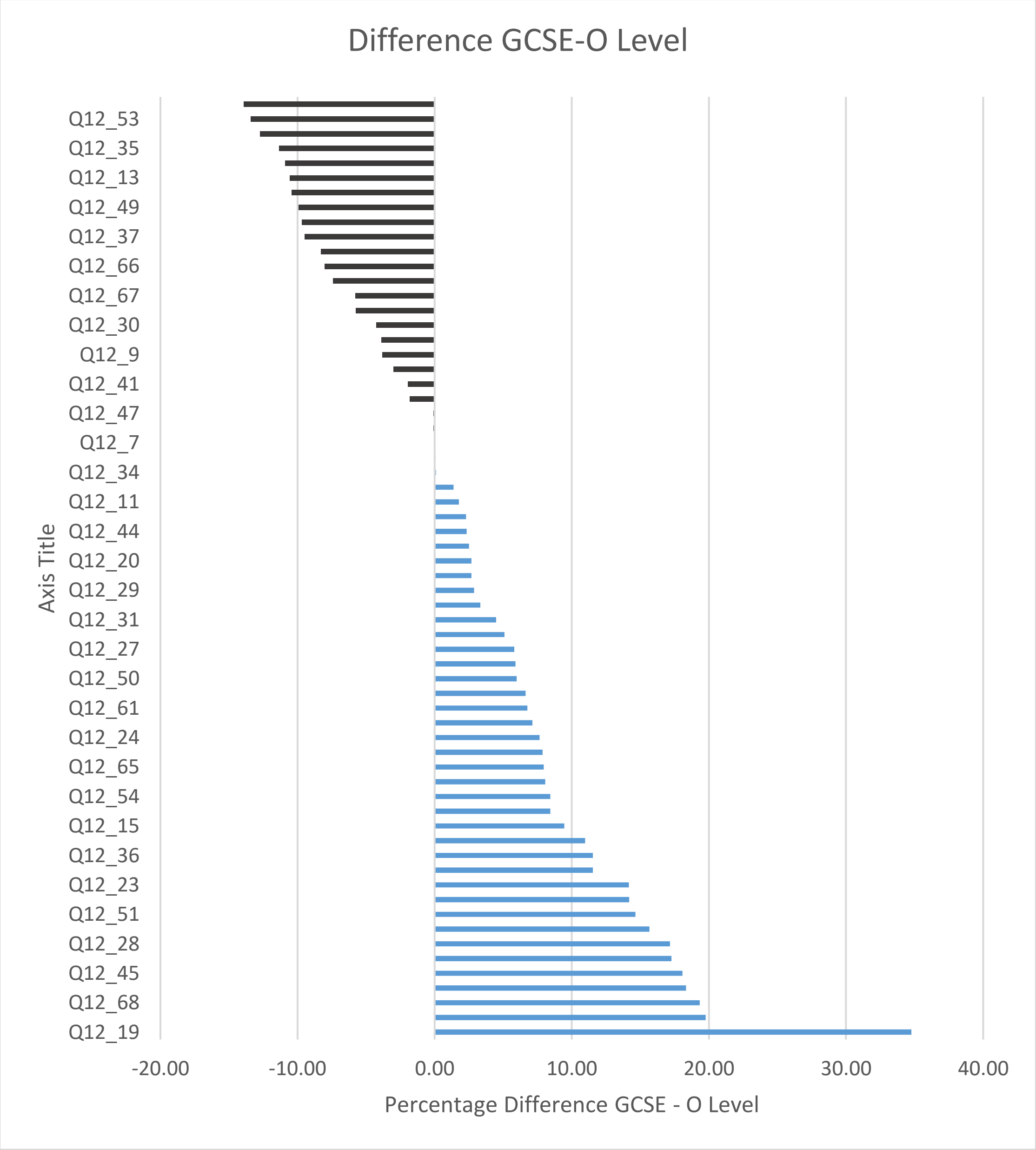


Figure 6-8: Learning Profile – Comparison of O Level to GCSE system

Table 6-9: Comparison GCSE Respondents to O. Level Respondents

Q12	Physicists only GCSE> O Level	GCSE	O Level	Diff	p
12_19	Academic / geek / nerdy	71.43	36.67	34.76	0.00
12_63	Hard working - put in the effort	67.53	47.78	19.75	0.00
12_68	Good at Mathematics	83.77	64.44	19.32	0.00
12_17	Patient and persistent in your studies	46.10	27.78	18.33	0.00
12_45	Achievement motivated	55.84	37.78	18.07	0.00
12_33	Enjoyed working with mathematics	77.27	60.00	17.27	0.00
12_28	Liked to be rated as clever	64.94	47.78	17.16	0.00
12_25	Methodical	62.34	46.67	15.67	0.00
12_23	See a task to the end	44.16	30.00	14.16	0.00
12_51	Worked quickly through calculations	51.30	36.67	14.63	0.00
12_48	Loved equations and formulae	59.74	45.56	14.18	0.02
12_36	Liked iterative nature of building understanding	33.77	22.22	11.54	0.01
12_22	Learning and studying strategies	33.77	22.22	11.54	0.00
12_8	Liked a challenge	72.08	61.11	10.97	0.00
12_15	A good head for facts	53.90	44.44	9.45	0.04
12_4	Work hard to understand physics	33.12	24.44	8.67	0.03
12_54	Liked talking physics/mathematics/ engineering	58.44	50.00	8.44	0.01
12_24	A problem solver	79.87	72.22	7.65	0.02
12_65	Helped others with understanding physics	51.30	43.33	7.97	0.00
12_21	Loved to study	34.42	27.78	6.64	0.02
12_50	Physics makes the world a better place	33.77	27.78	5.99	0.02
12_31	Work independently	73.38	68.89	4.49	0.00
12_44	Deal with complex/ambiguous concepts/questions	62.34	60.00	2.34	0.05

The GCSE cohort were significantly different in reporting more frequently on positive learning behaviours and learning competences for 23 of the indicators. The remaining indicators showed that both groups were comparable in reporting on their levels of Physics Identity, Physics Competences and Advanced Cognitive Performance. The largest difference score indicator was chosen by the younger, GCSE cohort, to describe themselves as academic / geek / nerdy at 71.43%, compared to 36.67% for O Level respondents. These terms are much respected currently and in 'trend' therefore these are positive statements whereas this may not have been the case in the past during the O. Level examination years. The statistical analysis showed only 2 indicators with a sig. diff. p< 0.05 which the O Level cohort chose more frequently. These were : They liked experimental work and they were ideas people, reflecting and playing with ideas.

Table 6-10: Comparison O Level Respondents to GCSE Respondents

Q12	Physics O level > GCSE	GCSE	O Level	Diff	p
12_29	Inventive	30.52	44.44	-13.92	0.06
12_53	Liked physics explanations of everyday life	61.04	74.44	-13.41	0.22
12_58	Novel ideas to problem solve	19.48	32.22	-12.74	0.24
12_35	Building mental models - seeing with your mind's eye	33.12	44.44	-11.33	0.93
12_40	Enterprising - thinking differently and striving to improve	16.88	27.78	-10.89	0.36
12_13	Good at abstract thought	38.31	48.89	-10.58	0.35
12_42	Ideas' person, reflecting and playing with ideas	24.03	34.44	-10.42	0.05
12_49	Got a buzz out of physics	46.75	56.67	-9.91	0.23
12_39	Innovative -solved questions differently to others	29.22	38.89	-9.67	0.52
12_37	Resilient to set backs such as getting the answer wrong	30.52	40.00	-9.48	0.87
12_14	Liked science experiments	69.48	77.78	-8.30	0.01
12_66	Unconsciously use key knowledge	25.32	33.33	-8.01	0.45
12_62	Observant - you had an eye for detail	44.81	52.22	-7.42	0.75
12_67	Initiative in lab work and problem solving	25.32	31.11	-5.79	0.76
12_64	Physics intuitive -understanding phenomena came with ease	40.91	46.67	-5.76	0.98

6.5 Summary – Learning Profile

A Physics Learning Profile was determined with a set of distinct Learning Characteristics, Learning Competences and Physics Identity. With a 98.6% STEM respondents the Learning Profile was examined in terms of Physicists compared to all STEM respondents. Examining the Indicators which were chosen by more than 50% of Physicists and STEM respondents showed no significant differences between the two groups at $p < 0.05$. level. However for those Indicators for which Physicists were significantly different from STEM respondents and at response levels less than 50%, the Physicists' Learning Profile had its own additional set of learning characteristics and competences- notably, resilience and resourcefulness, automaticity of prior knowledge, procedural competences, creativity of novel ideas and the capacity and drive to play with and reflect on ideas.

The Learning Profiles showed significant differences between males' and females' responses . This is an important finding on how STEM and in particular physics should be presented in a way that takes into account the differences in identity markers of female and male students. Currently the presentation of the qualities needed for physics study are akin to those characteristics most often chosen and by males and not the characteristics most often chosen and expressed by females of equal academic attainment.

The age range of participants crossed two examination periods, O Level and the more recent GCSE. Focusing on Physicists, the younger GCSE cohort were significantly different in reporting more frequently on positive Learning Characteristics and Learning Competences for 23 of the indicators. The remaining indicators showed that both GCSE and O Level cohorts were comparable in reporting on their levels of Physics Identity, Physics Competences and Advanced Cognitive Performance

Comparing Physicists with the rest of respondents according to STEM degree choice showed in the case of Engineers, where the number was sufficient to analyse significance, there were differences in choice of cognitive competences: Physicists more often responded that they were not put off by complex or ambiguous concepts and questions; good at abstract thought; key knowledge comes to mind unconsciously and they found physics intuitive.

Chapter 7 : Results and Discussion – Other Factors for Success in Physics

Chapter 6 presented the Learning Profile of the respondent population of Physics Learners. This was an overview of the Physics Identity, Learning Characteristics, Learning Competences and Cognitive Competences employed by the Physics Learner in doing physics. This chapter examines these in more depth as the factors which create and enhance efficient and successful learning.

How well one masters studying and attainment in a subject depends not only on intellectual ability but also a person's perception of their ability, aptitude for learning and identity as a learner. This was summarised in two Dimensions of Learning – Emotional and Social – and the External Interaction of a learner as defined by Illeris (2003) and discussed in Section 1.2.1 and summarised in relation to this study as:

1. Emotional Dimension: Perception of Ability, Self-Assessment of Performance and Physics Identity
2. Social Dimension: Learning Behaviour, Communication and Co-operation in learning.
3. External Interactions: Classroom Behaviours; Peer Groups and Home Influences; School Environment

These Dimensions and Interactions were addressed in the following questions:

Q19: Respondents asked to, select all that apply, from a list of 16 Learning Characteristics in physics lessons, 7 items which focused on Perception of Ability, Performance and Achievement.

Q20: Select from a list of 11 descriptor of Physics Identity.

Q21: Select from a list of 12, those factors which may have influenced students to choose Advanced Level physics at school.

The analysis for the data in these questions is not addressed in the order of the Q19,20,21 as they appeared in the questionnaire but rather Q21 and the factors which influenced choosing to study A level physics is covered first and then Learning Character. Reference to Physics Identity is made throughout and therefore results for Physics Identity are discussed first.

7.1 Physics Identity

Physics Identity was defined by Potvin and Hazari (2013) as;

- the desire to learn physics,
- one's self perception of an ability to do physics,
- one's perception of the assessment by others of the ability to do physics
- self-efficacy, the personal judgement of one's ability to take courses of action as required in the dong of physics.

Figure 7-1 shows the percentage frequencies calculated for the whole population of 657 respondents in their selection of descriptors of Physics Identity.

Note that the most important factor in Physics Identity is that others recognised the talent of the student (51%). On the other extreme 9% reported that they were indifferent to the views of others. This statement on indifference to the views of others had been included in the question as a measure of Uncertainty Orientation (defined by Sorrentino and Roney 1999) and used by Hanze and Berger (2007) in their study of motivational and learning characteristics of 12th form physics students and in this context appears as a mark of academic resilience.

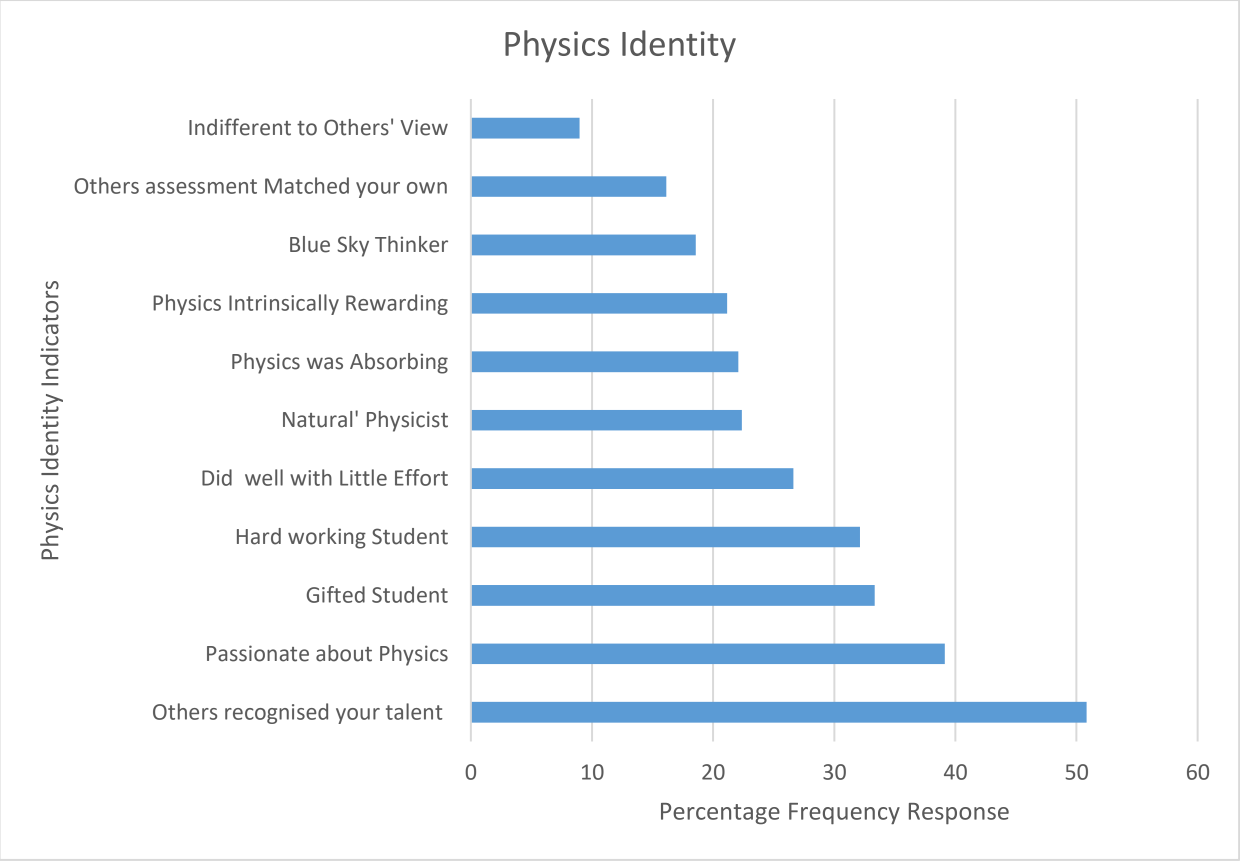


Figure 7-1: Physics Identity Ranking of Indicators

Table 7-1: Physics Identity Indicators

Full Indicator Description	Abbreviated Indicator
You were the 'go to' person for anything physics related - sure to understand and explain.	Others recognised your talent
Irrespective of your exam grade you were passionate about physics	Passionate about physics
You were a gifted student with great potential	Gifted Student
You were a solid, steady, hardworking student	Hard working student
You were able to do well without much effort	Did well with little effort
You were a 'natural' physicist	Natural physicist
Doing physics was highly absorbing	Physics was absorbing
Doing physics was intrinsically rewarding	Physics intrinsically rewarding
You could be described as a Blue Sky thinker creating compelling and original ideas.	Blue Sky Thinker
Others (teachers , peers, parents) also rated you in this way	Others assessment matched your own
You were indifferent to how others viewed you as a student	Indifferent to others' view

7.2 Choosing to Study Physics A Level

Considering that the number of students who chose at age 16 years to study physics is low, and in the case of girls only ~ 20% of physics students are female, examining the factors which influence uptake of the subject merits serious examination. This underrepresentation of girls is significant. The Higher Education Careers Service Unit HECSU (Montgomery 2020) have calculated that if the gender imbalance was addressed it would produce 1.2 million females physicists as opposed to the current 462,000 in the UK.

Figure 7-2 shows that being ‘good at physics – good grades’ which refers to achievements in the classroom rather than examination attainment was the most often chosen (69%), this feeds into the reassurance that success is secured and therefore studying physics is a worthwhile option.

The second most selected influence was enjoying and being fascinated by physics, 65%. While wishing to enter a physics or engineering related career was chosen by 60% and physics opens most career opportunities at 27%, would indicate the importance of making physics related career options more well known. Being encouraged by a teacher or the school was also very important at almost 42%.

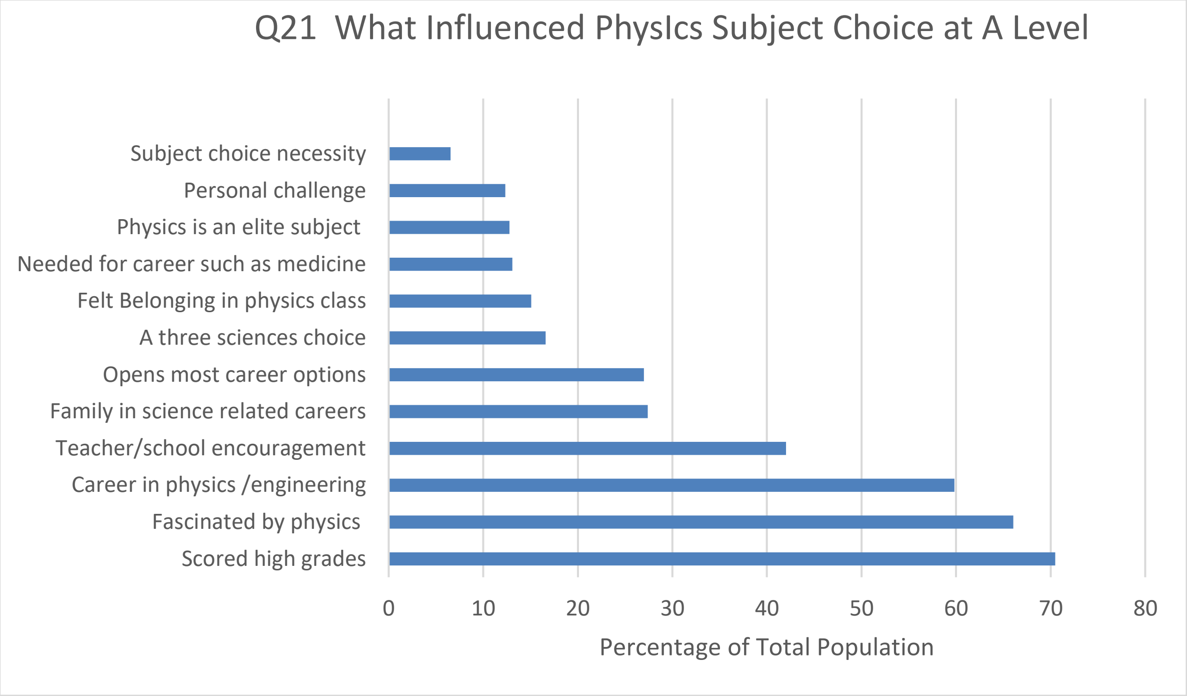


Figure 7-2: Influences on the Choice of Physics at A. Level

All of these influences had shaped or supported the Physics Identity of the former student respondents. The student's self-recognition as a physicist was strengthened through peer and school encouragement and that they could see themselves having access to physics related careers, others saw them as future physicists, scientists or engineers and they felt that they belonged to the physics class. The negative impact of the absence of these positive drivers is discussed Chapter 8.

7.3 Classroom Learning Characteristics

Figure 7-3 shows that the physics classroom characteristics for the population indicated high levels of engagement, greater than 35%, for 7 out of the 10 characteristics relating to the social dimensions of learning - communication and co-operation. These included: asking and answering questions, taking part in physics discourse, tutoring others and listening with intent, which are all part of the competence Representation. Figure 5-5, discussed in Chapter 5 on Physics Competences, highlighted Representation as the competence mastered most often with Ease by those respondents who achieved the higher A*A,B grades at A level. Leading physics educationalists Simon and Norman point out the importance of Representation "*for if the representation and the processes are just right, then new experiences, insights and creations can emerge*" (as quoted by Van Heuvelen1999). Therefore these classroom characteristics are deemed to be important and to be encouraged.

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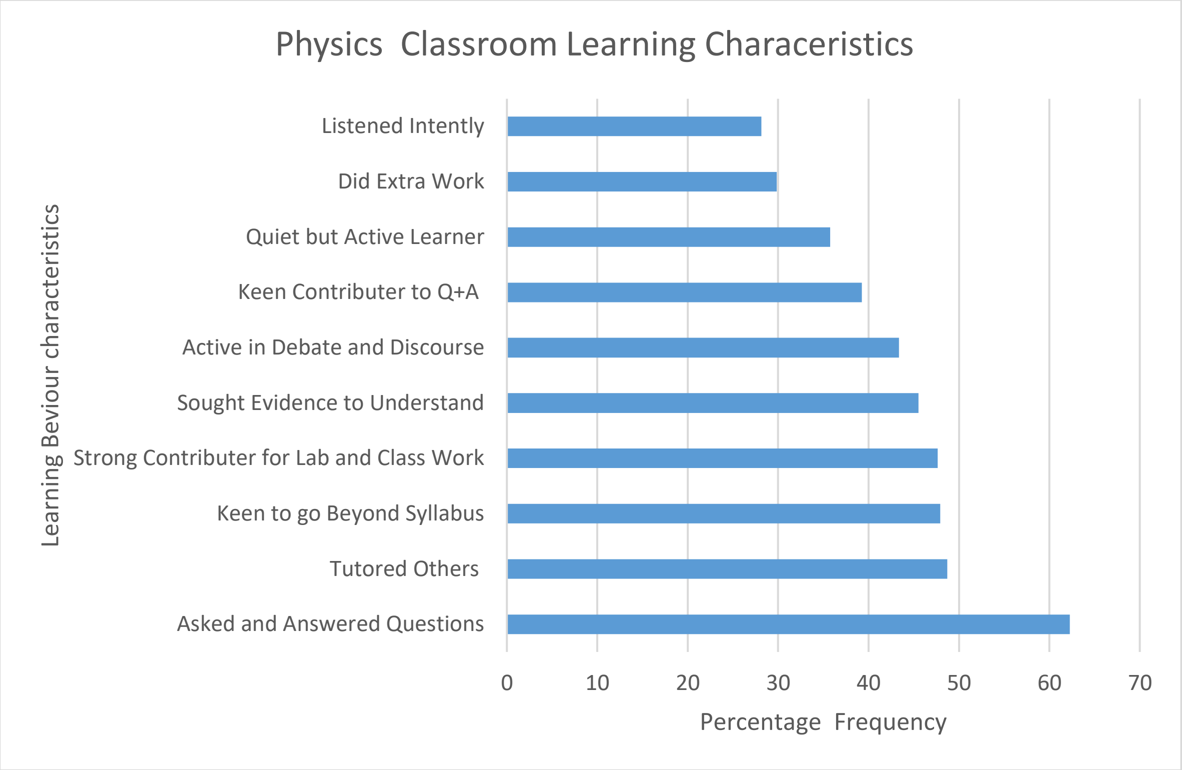

Figure 7-3: Classroom Learning Characteristics

Table 7-2: Classroom Learning Characteristics Indicators

Full Indicator Description	Abbreviated Indicator
You were competitive i.e. Liked to score high in homework and tests.	Competitive
You usually asked and answered questions	Asked and answered questions
You helped other students with their work and understanding of physics	Tutored others
You were keen for the teacher to go beyond the syllabus or to more depth.	Keen to go beyond syllabus
You made a strong contribution to lab work or demonstrations	Strong contributor for lab and class work
You questioned and sought evidence to ensure you understood rather than learn off.	Sought evidence to understand
You took an active role in discussion and debate	Active in debate and discourse
You were a key contributor to questions and answers	Keen contributor to Q+A
You were quiet in class but actively working to get to your own level of understanding	Quiet but active learner
You read beyond the syllabus /did extra questions	Did extra work
You listened intently during lessons	Listened intently

7.3.1 Learning Characteristics and Strategies

Eyre (2016b) described the Learning Characteristics and strategies of High Performance Learners. These were used to produce the Indicators shown in Figure 7-4. The following characteristics and strategies were chosen by over 50% of respondents: They were aware of their own strengths and weaknesses and adjusted their work to continue to achieve accordingly. They consistently worked to improve their performance and were keen to better their understanding of physics, taking on deliberate practice as required. Since ~70% of respondents achieved grades A*,A, B at A level, these choices match expectation, however a more diverse academic group of respondents would be needed to identify and distinguish any differences in levels of learning characteristics and strategies.

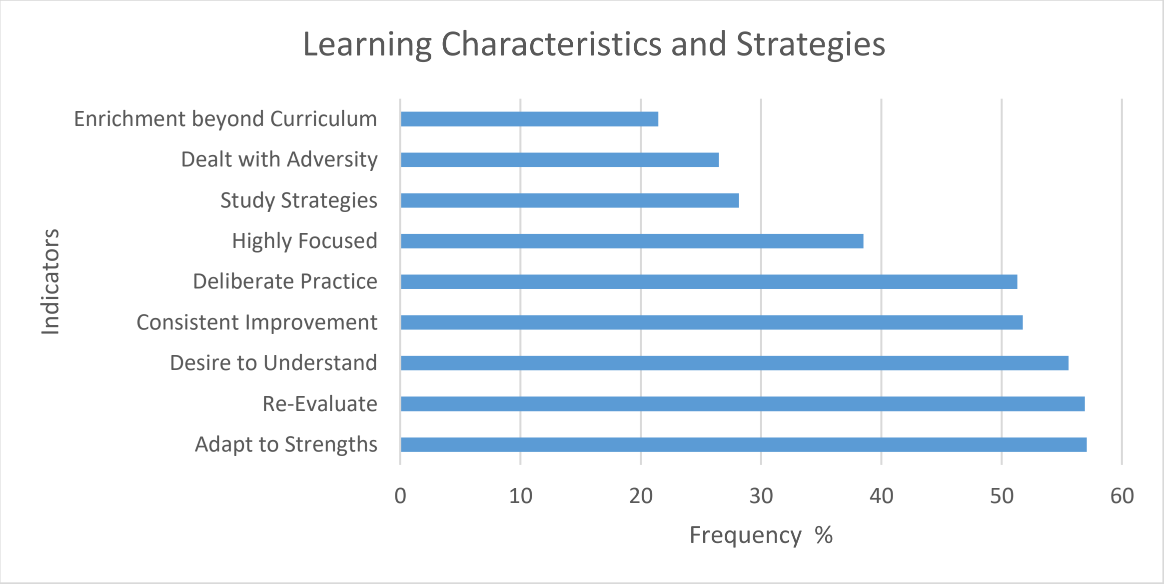

Figure 7-4: Learning Characteristics and Strategies

Table 7-3: Learning Characteristics and Strategies Indicators

Full Indicator Description	Abbreviated Indicator
Aware of your strengths and weaknesses and adapted accordingly to improve performance	Adapt to strengths
You would check back, re- evaluate and re-work your notes and homework	Re-evaluate
It was very important to you to really understand the physics	Desire to understand
Consistently seeking ways to improve	Consistent improvement
You did solitary, deliberate practice	Deliberate practice
You could achieve high levels of concentration and focus	Highly Focused
Managed your time well for study, revision, monitoring progress	Study Strategies
Able to process in spite of adversity in your life	Dealt with Adversity
Took part in enrichment activities such as Science Club, Physics Olympiad, Nuffield Research Placements CREST Awards etc.	Enrichment Beyond the Curriculum

7.4 Ability, Performance, Attainment

Figure 7-5, reading the graph from the bottom to top, gives the respondents' self-assessment of their student ability (2 measures), performance (2 measures) and attainment (4 measures). These figures were calculated as percentages of the total population of respondents and reported across the full age range and academic attainment.

Almost one fifth of respondents (18.7%) considered that they had underestimated their ability in physics. Whereas 16.5% believed that they had underachieved. Close to one fifth (19.17 %) considered that they were good enough at physics.

These are important findings as they come from the reflective assessment of a mature, high-achieving population with a high level in education experience. The findings also correspond with the work of other researchers who have examined the impact of Physics Identity as academic self-concept and stereotype threat (Bong and Skaalvik 2003; Helmke and van Aken 1995) on academic performance behaviours. Both these factors, positive academic self-concept and stereotype threat in turn facilitate or hinder the learning processes.

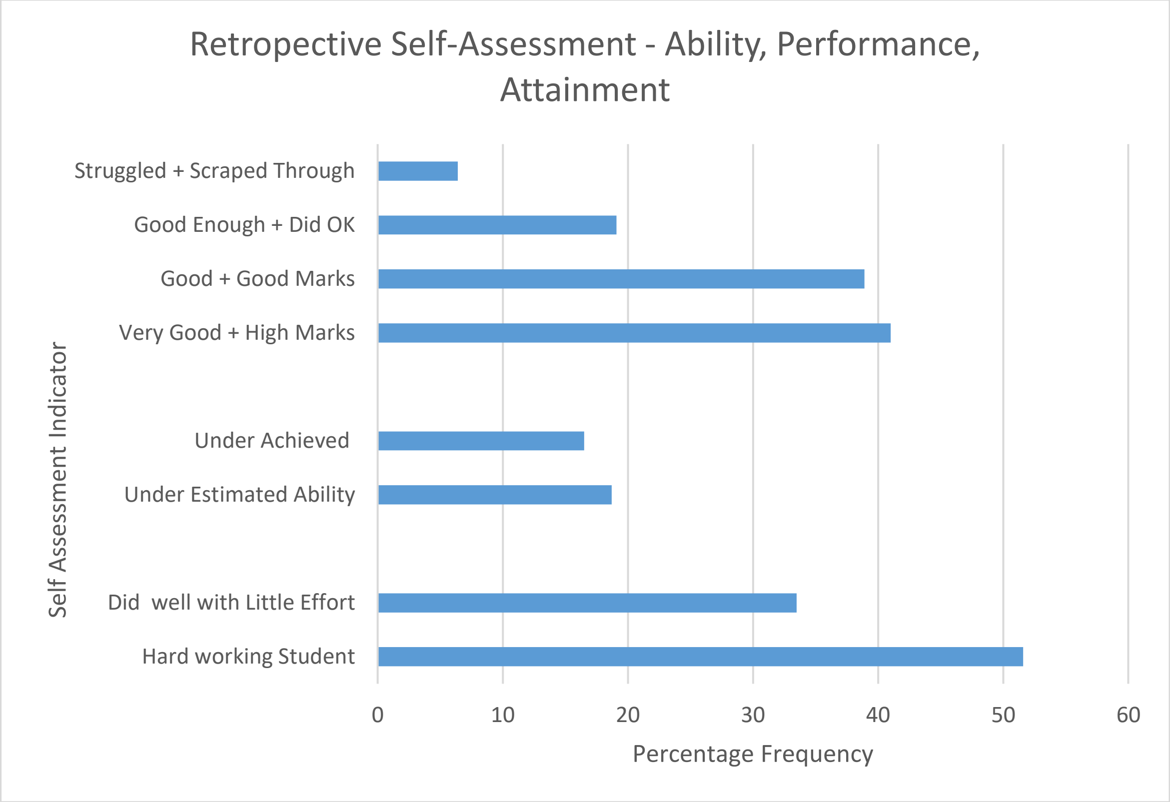

Figure 7-5 Self-Assessment of Ability, Performance and Attainment

7.4.1 Under Estimation of Ability

The retrospective assessments of physics ability for 18.7% of respondents, shown in *Figure 7-5* is that they considered that they had underachieved. In setting the question, this underestimation was considered to be a proxy for low Physics Identity which may have affected intellectual confidence and therefore may have lowered performance and attainment (Bong and Skaalvik 2003; Helmke and van Aken 1995). However this was not borne out in attainment. Those who felt they had underestimated their ability, had achieved at GCSE 74.4% grades A*A, with the lowest grade being D for only 0.8%. They also achieved at A Level 53.7% A*A and the lowest grades of E and F were 5% and 0.8% respectively. Career-wise this group were also successful, represented in keeping with the overall statistics across all the career options with 6.6% in University Physics, 6.1% in R+D and 35.5% in Engineering, Technology and Manufacturing businesses or industry. Therefore the response is more a statement of how well they had achieved; something the respondents had perhaps not expected as likely as a school student. The response is very important in the intricacies of understanding the experiences and modus operandi of succeeding in physics. Almost one fifth, 18.7% of the respondents, had selected this option which means that although they had succeeded in gaining a physics qualification, they had experienced at the time a doubt of their ability to do physics. This experience was shared equally among female and male respondents.

7.4.2 Underachievement

In Q20, statement 3 was: *You had the ability but did not apply yourself and underachieved.* 16.5% of respondents felt that they had underachieved. This response showed, on examination, a gender bias and two possible interpretation of underachieved- a) a drop in grade at A level, b) achieving a high grade but without the opportunity to give that subject and its study a full commitment or a commitment to one's own set of standards. The features in responses were:

- A drop in grade attainment from GCSE/O Level to A level
- The lower grades of C-E were all achieved solely by males.
- The top grade A was achieved solely by females, 11% of the total
- Grade B was achieved by 34% of respondents, 83% female.
- D and E grades made up 31% of these respondents

Table 7-4: Comparison of A level Grades for the O. Level and GCSE Cohorts

	% A	% B	% C	% D	% E
GCSE/ O Level	60	31	9		
A Level	11.4	34.1	23.9	18.2	12.5

Achieving grade D and E are understandable measures of underachievement for students who achieved grades A, B, C at GCSE/O. level. Accounting for this underachievement respondents cited: loss of good teachers, school reorganisation, lack of effort when not adapting to the jump from GCSE level, distraction of life outside and family break ups.

However to understand why the females who scored grade A at A. level would still describe themselves as underachievers at school, the narratives of Q21.a (*Were there challenges that you had to overcome or pressures to resist to stay on course with your physics study)* were examined. Upon investigating this data it would appear that the female high achievers felt they were underachieving during their studies because they were conscious of the challenges they were working under. They reported that they were working against a resistance and so they did not experience any ease of achievement. The challenges reported were the psychological and emotional pressures related to the need to feel wholly supported. These included; being the only girl in a class of boys and feeling isolated, being the first at home to aim for university and dealing with parental resistance to time spent studying, moving from an independent school environment to comprehensive and missing a greater level of learning support, and interruption to studies during a time of family break up.

It was interesting to note that those achieving the E and F grades were subsequently high achievers, and their low performance could be related to adverse conditions during the A level study period of their lives, however the sample size was very small.

Table 7-5: Grades E and F and Progression to Higher Education in Physics

Age Range	Grade E	Grade F	Progression
36-45	1		HND - Degree
46-55	1	1	2 PhD
56-65	4	1	1 HND, 2 BSc, 2 MSc,
66 -75+	1		Degree

7.5 High Performance Physics Identities.

There is a certain familiarity with the terms gifted physics student, natural physicist and Blue Sky Thinkers (strong ideas innovators) among the STEM community. These high-performance descriptors would suggest to be measures of strong Physics Identity but are they true measures of physics academic attainment? Figure 7-6 and Table 7-6 and Table 7-7 show a measure of the usage of such terms among the respondent population and the correlation with academic attainment.

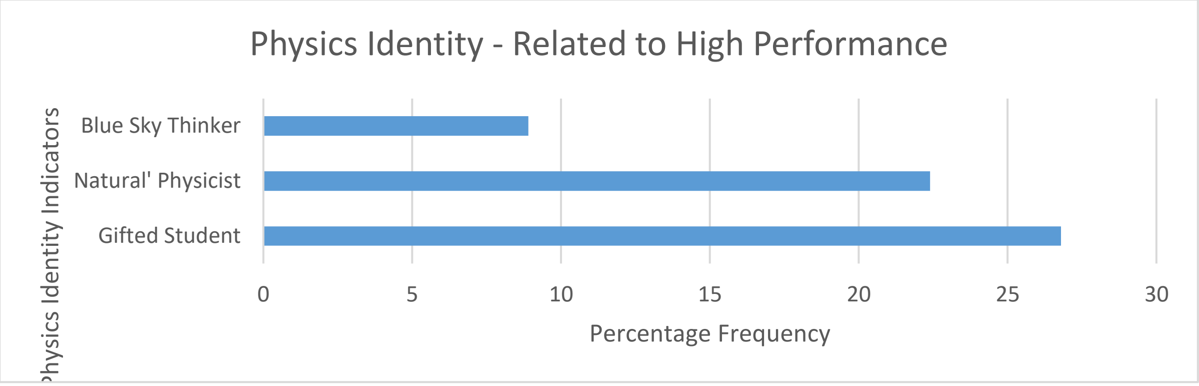

Figure 7-6: Physics Identity – All Respondents

Table 7-6 shows that these terms are particularly popular among Physicists with 40% describing themselves as gifted and/or natural physicists and ~ 23% as Blue Sky thinkers. The usage of the terms have gender equity. Among this groups 51% found physics intrinsically rewarding and 40% found it to be highly absorbing. Of those who considered themselves to be 'natural physicists ', 70% continued with their physics studies to become physicists. The remainder had careers cross the full spectrum of career categories including Medicine, Health and non-STEM.

Table 7-6: Self-Assessment as Exceptional Achievers

Strong Physics Identity Descriptors	%Male	%Female	% Physicists	% non-Physicists	% All Respondents
Blue Sky Thinker	55.4	44.6	23.1	0.00	8.9
Natural Physicist	48.6	51.4	40.8	10.8	22.4
Gifted Physics Student	48.5	51.5	39.4	19.9	26.8

With regards to academic attainment at A level, it was interesting to find that those who described themselves as Blue Sky Thinkers, Natural Physicists and Gifted Physics Students did not all have the top grades of A and B and in fact attainment spread across the full grade range as shown in Table 7-7. Many of such respondents who might be regarded as ideal physicists, many had achieved low grades and this merits further investigation.

Table 7-7 Strong Physics Identity: A. level Grades

Physics Identity vs A Level Grades	%A	%B	%C	%D	%E	%F
Blue Sky Thinker	12	22	17	27	14	
Natural Physicist	29	26	17	20	7	0.6
Gifted Student	27	27	18	18	7	0.5

7.6 Summary – Other Factors of Success

The most important influences for choosing to study physics A Level were; achieving good grades and good marks in class and homework; enjoyment of the subject and career ambitions or opportunities.

Physics Identity is an important support or enabler to learning, with recognition by others as being ‘physics able’ the top identity marker.

Classroom behaviours which support learning were identified as strength in communication and collaboration, such as participating in asking and answering questions, debate and discourse and tutoring others. These are means of strengthening the Representation competences, consistent with the findings in Chapter 5 where the highest achieving respondents where those who scored high on mastery of Representation Competence.

Learning strategies that were the most frequently selected were: being highly focused, the ability of achieving high levels of concentration, partaking in deliberate practice, self-evaluation and dealing with uncertainty.

It was found that even students who achieved high A Level grades, and girls in particular, felt they had underachieved at physics and others who had not achieved high grades considered with hindsight that they had underestimated their ability.

High performance Physics Identities such as gifted, inherent or natural physicists, Blue Sky thinker occurred frequently - a quarter of all respondents- and as high as 30-40% among Physicists. However these strong physics identities did not correlate totally to high attainment. 50-60% attained A, B grades while the remaining respondents in this group achieved grades C-F. Hence as many as 40% of respondents in the lower grade group considered themselves as very good physicists in spite of the grades.

Chapter 8 : Results and Discussion – Phenomenographic Analysis

The questionnaire had three narrative style questions which explored the factors that challenged or facilitated the learning of physics, as experienced or discerned by the respondents. By relating their personal perspective of learning to the research, respondents were involved in a phenomenographic process. Phenomenographic analysis has been described in Section 3.5 to produce Themes (highlighted blue cells in tables of results) and Codes (white cells). The codes produced can be considered to equate to emic descriptions (‘experience-near’ concepts) that describe the meaning of the respondents experiences of learning, as discussed here. The questions were:

Q19-a. If you were part of a minority set within the class, did this have any impact on your learning, positive or negative? Describe the minority set and the impact.

Q21-a. Were there challenges that you had to overcome or pressures to resist to stay on course with your physics?

Q21-b. Considering your childhood play, hobbies, your upbringing and experiences of your youth, are there any aspects that you would now consider improved your ability to do physics.

These open questions allowed the respondents to provide a narrative of their personal physics related story and also to give their insights and considered opinions on how to succeed in physics. Henceforth the three questions are referred to by the abbreviated title Minorities, Challenges, Heuristic Learning.

The response level for each Question was	N	% of 657 total
Q19a Minorities:	154	23%
Q21a Challenges	189	29%
Q21b Heuristic Learning	360	55%

In the code tables the number of references per code is given as (n)

8.1 Minorities

Table 8-1: Codes for All Minorities

Codes (n)	MINORITIES
	No Impact within minority groups
No Impact (49)	No comment on positive or negative effect of minority
Demographics (23)	Social aspects, ability, race or sexual orientation.
Nerds (11)	Happy to be different and just get on with it - the science mattered most – most likely to have decided on further physics study
Females (118)	In a minority of females

Codes (n)	MINORITIES
	Positives within minority groups
Attention (3)	Advantage of extra teacher attention
Strengthened (27)	Minority status built up competitiveness. Identified resilience or confidence they considered necessary to succeed in physics
	Negatives within minority groups
Peers (17)	Isolated as considered ‘weird’ for liking physics. Girl not able to discuss physics with the boys. Unease to partner with boys in class.
Classroom (27)	Girls felt overlooked in class. Teacher focus on the boys. Mostly male perspective in discussions of physics. Sexist remarks. Laddish behaviour. Teacher and other students believed that girls not as good at physics.

It was found that almost a quarter (23.4% n= 154) of the respondents, reported that their study of physics was impacted by being part of a minority. This was made up of 8.3% of the total population of male students and 36% of the total female population. It is important to note this figure of 36% of females of a population of 657 respondents had experienced being part of a minority and the majority of these experiences were of challenge to varying degrees.

The minority groups fell into three categories:1) Those who self-reported being in a minority ‘nerd’ group, who set themselves apart to immerse/ excel in the subject 7%. 2) Another 15% who were in a minority due to demographics; ethnicity, social class, students who had come through non- traditional routes and students of lower academic ability in a strong academic ability class and vice versa. 3) The remaining 78% reported impact related to gender issues, all female. This minority gender group of girls were often lone girls or small groups of 2/3/4/5 in classes of range 9-25 students.

Table 8-2: Impact of Minority Status on Learning – All Minorities

Group	Percentage of Total Response	Impact	Ratio Number Male: Female
Nerds	7%	100% Positive	7:1
Demographics	15%	35% Positive	14:9
Females	78%	22% Positive 37% Negative 41% Neutral	0:1

Table 8-2 shows that a minority status for male students is more often positive for their learning. Overall it was females who felt that they were impacted less favourably by their minority status.

The 37% who experienced negative impacts were very clear that the impact their minority status as females had deterred learning and success. 22% reported a 'positive impact'. The positive effects were the development of resilience and academic confidence that would sustain them as they continued in a minority gender set in further study or career. A set of armour which their male peers would not have to develop. 41% of females in this minority reported no effect but many qualified their responses by describing themselves as different from other girls, already resilient or high achievers and thus having academic respect as being 'as good as the boys'.

Some females reported being top of the class and out-performing their male counterparts, thus 'owning' their place. Other expressed the feeling of representing all females so that it was important to do well, not just for their own success but so as not to let the female side down. But these feelings of needing to actively counter a stereotype or develop resilience are adding a social load for female students in addition to the academic load, a situation which their male counterparts do not need to deal with.

For all minority groups the percentages who reported positive, negative and no impact on their learning due to their minority status the results are summarized below in Table 8-3.

Considering how these effects may have impacted grades, the percentage within each group who achieved grades A* A or B are given. There appears to be a correlation between reported negative impact and grade attainment. Although there would be other factors which may have had an effect on A level grade (as is documented and discussed by the IOP and others, section 1.1.2) but this would be applied across the board. Also worthy of note, some respondents did draw attention to the fact, that in spite of the negative impact on their learning experience they still achieved high grades through compensatory hard work.

Table 8-3: Impact of Minority Status on All Groups

Impact for All Minority Groups		
Positive	No Impact	Negative
28% of minority set responses	32% of minority set responses	40% of minority set responses
6.5% of all responses	7.4% of all responses	9.4% of all responses
% Achieving Grade A*A or B in Each Category		
88%	58%	65%

Further examination of coded responses explored what reasons were given as the cause of the negative impact on learning and how some students were able to gain some benefit from their minority status and experience. These are set out in the categories of quotes below.

Negatives for Female Students:

Teachers and school management displayed stereotypical biases such as sexism, subtle and overt exists, manifest in teacher comments and 'lad humour'

> *I think my teacher was surprised I got the highest grade, he had low expectations?*

> *I was the only girl in the class of about 20. There was often a bit of a 'lad's culture' and in group work they tended to work together. The second year of the A-level, after I had gained the top marks in the class at AS level that changed.*

Female students were limited in their learning because they felt shy or ill at ease about asking or answering questions in their minority status environment. Some felt isolated in and outside the classroom - They were on their own as the boys stuck together; no partner for practical work, no opportunity for peer-to-peer learning and therefore attainment was limited or harder to achieve as a lone student. Without this peer involvement girls didn't feel they belonged

Outside the physics classroom they were isolated due to the different timetabling away from the other girls. Other girls considered them 'weird' for doing physics and for being on 'talking terms' with the boys.

Academic bullying was identified as an atmosphere loaded with the stereotypical view that girls cannot be good at physics, or needing to reduce their interest in physics when with the less engaged or non-physics girls.

> *The girls would sit together. I had male friends in the class who would be more actively involved in the lesson, and I feel now that if I had sat with them I would also be more actively involved. But I didn't feel as though I could move over to where the boys sat as it would be 'weird'.*

> *Male teachers and a boys' club atmosphere made it harder to ask for help.*

With hindsight they saw that they had altered their career expectations because of the stereotype pressures and low academic expectations for females in physics.

Positives for Female Students:

They felt they had to prove they were as good as the boys so they worked harder. In doing so and pressing themselves to be involved in lessons, holding their ground resulted in gained resilience and confidence. It prepared them for the journey ahead; again indication that they expected to be part of a biased, gendered system. So although these are positives they are an extra stress for female students to engineer and manage compared to their male counterparts.

Similarly some respondents stated that there exists a pressure for female students to carry the responsibility to defend the academic reputation of their gender.

> *I was one of two girls and I felt like I always had to be the best because I was representing a whole gender rather than just me*

The same sentiment was expressed in the negative as well; female students had felt their status was part of an unjust system and any under-performance by them impaired the reputation of girls in physics. Whereas it could be said that the converse would be to the advantage of boys, knowing that at least they were better than a girl. This was directly expressed by one respondent as

> *I was the only girl in all my A level science classes. I often had to deal with the boys saying "even J can understand this".*

8.2 Challenges

There were 166 responses to this question which accounts for 25% of the total number of respondents. Three themes emerged:

Theme 1 Challenges- within the subject and curriculum matters

Theme 2 School - school imposed hurdles

Theme 3 Motivation – Effect on motivation and engagement

These themes and the corresponding codes are set out in Table 8-4 and discussed thereafter.

Table 8-4: Codes for Challenges

Codes (n)	CHALLENGES
	Challenges
Step-Up (33)	The increase of difficulty from GCSE/O Level to A Level
Maths (20)	Not studying Maths A level or finding Maths aspects difficult
	School
Teacher (24)	Poor teaching, biased teachers , syllabus not covered , modules not supported , no enthusiasm
School (19)	Discouraged from studying physics Minorities not supported adequately
	Motivation
Confidence (7)	Doubted their ability
Home (19)	Non science family, discouragement to studying physics- such as career prospects

	Motivation
Isolation (12)	Isolated from friendship groups, bullying mostly experienced by minority groups – mainly girls – different type of learner such as autism
Distractions (Including Health) (32)	Music events, part time work, preferred other subjects. school work overload , lack of effort. Mental health problems. Reading difficulties – Dyslexia. Physical or mental health problems (depression), turmoil at home, dying parent or death in family.

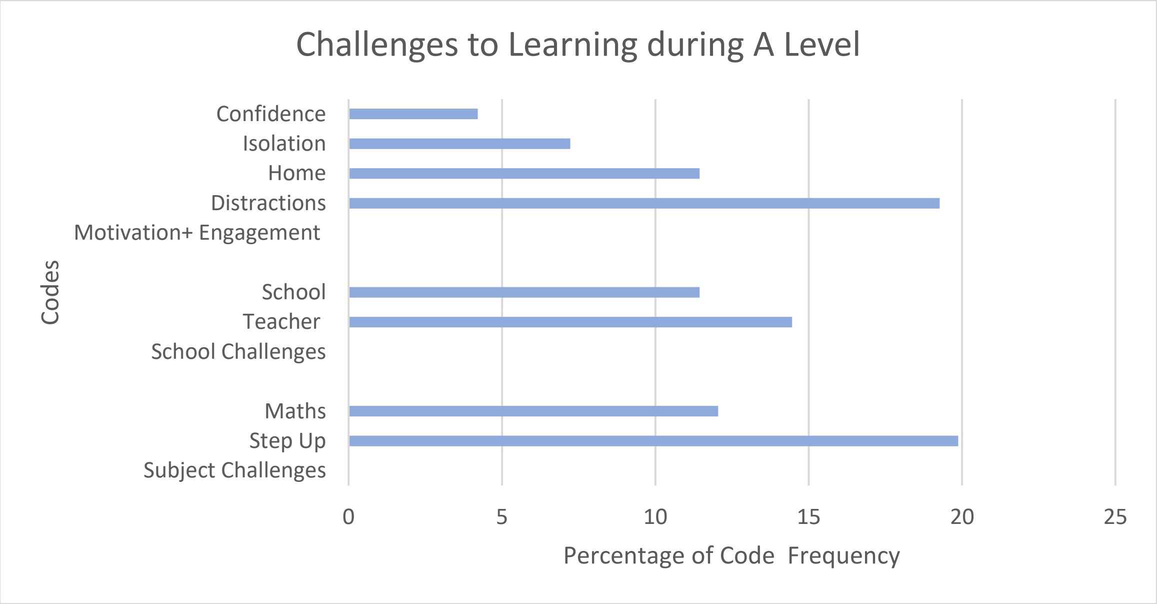

Figure 8-1: Challenges to Progress at A Level

Theme 1- Challenges: References were made to the *Step Up* in subject difficulty from GCSE to A. Level and/or the course workload. Those who found *Mathematics* difficult or more often did not study A Level mathematics with A Level physics, stated this as a challenge and disadvantage. The increased workload was also reported as a significant challenge.

Theme 2- School: *Teacher* coded responses most often referred to poor or inadequate teaching, poor teacher student relationship, specialist physics teacher shortages. Beyond the classroom experience, some *School* challenges were; discouragement from school management staff or school policy on who should study physics or all parts of the course not being available or provided for.

School system challenges, such as or grade boundary pressures (that schools require students to get the high grades to continue on to A level physics and the known experience that many students enter A level with high grades at GCSE and face the prospect of attaining lower grades at A level) were identified and perhaps more keenly with the overview of an adult perspective

Theme 3- Motivation: On a personal level, respondents also identified the challenges they had experienced on their motivation and engagement due to teenage pressures and workload.

- *Confidence* in ability was an issue for some students even for those who were achieving well who may have felt they had to work very hard to achieve the grades.
- *Isolation* referred to loss of friendship groups because of studying physics. In part due to the correspondent timetabling differences. Or being part of a minority, was discussed in the previous section.
- The *Home* code referred to lack of encouragement from home or an appreciation of the subject and its value. This was a challenge for such students, some needing to justify their desire to study physics when the future outcome and opportunity potential was not understood. Respondents usually tallied this with being in a traditionally non- STEM family and parental concerns over potential future employment and suitable careers
- *Distractions* were a mix of the happy distractions such as the pull of the adolescent social life or another more favoured subject to concentrate on. Negative distractions were due to the weight of disruption of home and family life or physical or mental illness. Either way the focus on the study of physics was hampered.

Setting aside the 31% of challenges due to the Home environment and adolescent Distraction, all other issues could be addressed. These findings indicate the level of action required to redress the access to physics question

- Changes to school and classroom management,
- Greater subject appreciation to address the problems of poor teaching and negative school values in relation to physics.

Currently such challenges are under investigation in a whole school approach that has been piloted and promoted by the IOP,(IOP 2017b) in six pilot areas and schools in London. The pilot was designed from the work of the IOP and the longstanding research of Smithers and Robinson (2006). Currently in its second phase this pilot has shown improvement by creating a physics positive school culture resulting in improved subject uptake and achievement, nurturing the students to build academic confidence and physics identity.

8.3 Heuristic Learning

Heuristic Learning, differed from the other Minority and Challenges groups, which were school based and generally referred to changes needed or certain conditions required for success. Heuristic Learning is about the factors beyond school which respondents, with the benefit of hindsight, believed enabled and enhanced learning and doing physics.

This was considered important with regards to how more students might be encouraged or made ready to study physics. In particular would there be aspects of this heuristic learning that would be particularly beneficial in the drive to recruit more female students to continue with physics, more students from low socio-economic backgrounds or those of certain under represented ethnic groups.

For Q21b, in designing the question, the hypothesis was that some types of play, hobbies and home life experiences throughout youth could enable and enhance one's interest and ability to do physics. That is, the question invited the respondents to explore for themselves the heuristics aspects of their physics learning and doing, which would have occurred out of the school context, at home or as extra-curricular activities.

Considering your childhood play, hobbies, your upbringing and experiences of your youth, are there any aspects that you would now consider improved your ability to do physics?

The open nature of the question and its position at the end of the questionnaire was by design so that the engaged respondents, now within the mind-set of the questionnaire, could without much more effort, be able to narrate their personal heuristic.

The question received a large response with 360 respondents, 55% of the total population - 54% female and 46% male. Two themes emerged

Theme 1 : Play, Hobbies and Pastime Work.

Theme 2 : Upbringing Experiences.

66% of replies referred to the heuristic learning gained through specific activities carried out by the young people (playing with toys, hobbies, interests). 34% related to personal or parental endeavour towards learning whilst 11% referred to personal curiosity and 23% to family (this is upbringing or parenting style) which included encouragement to explore and learn, and engagement with the environment to satisfy scientific curiosity.

Play Although it is not within the scope of this study to research the psychology and learning outputs of play and recreational pursuits, it can be seen that there are two types of play referred to; that of the use of toys, most notably *Construction* toys, and in particular the assembly kit type toys such as Knex, Lego and Meccano.
Other toys and games such as jigsaw puzzles, board and computer games, science kits and reading. These are all purchased toys with recognisable learning aims. Other play is that of the inventive, creative outlets of tinkering, making, exploring and through these experiencing physics phenomena first hand. It is important to measure the contributions both types of play make to learning, considering that those underrepresented in physics may be also divided by learning opportunities in play. In particular , those from low socio-economic may not have the same level of access to educational toys and science outings.

Hobbies, Sport and Pastime-Work could be considered as a parallel or next stage learning process. They each encompass the inventive, creative outlets of tinkering, making, mending, repairing, exploring and experiencing physics phenomena throughout the process. Pastime-work is an important inclusion here as hobbies and sports are more accessible to students in medium to high socioeconomic backgrounds. Also young people may be required to work, rather than play or follow hobbies, for economic or cultural reasons.

Table 8-5: Codes for Play, Hobbies, Pastimes and Upbringing

Codes	PLAY, HOBBIES , YOUTH EXPERIENCES – UP BRINGING
	Play – Using purchased resources
Construction (66)	Mainly Lego, Knex, Meccano, but other construction kits and construction activity for the purpose of play. includes crafts and model making
Games (35)	Games - including computer games -Puzzles - Science kits
Tinkering (26)	Taking hard drives or mechanical thing and mostly toys apart. Respondents used the word 'tinkering' and 'taking apart'. Also Inventive
	Hobbies + ‘Pastime-work’
Reading (39)	All forms of reading not exclusively science books. Watching documentary or science related programmes
Electronics (32)	Amateur radio , computers, electronics accessed by interest rather than solely as a formal hobby
	Hobbies + ‘Pastime-work’
Music (12)	Playing a musical instrument
Computing (11)	coding – programming
Sport (6)	Cadets, Air Force , Out in nature (Informal Sport) - climbing trees , Sports - relating to the doing of sport
Work (26)	Farm work, DIY and repairs, Practical jobs at home
	Up Bringing Experiences
Curiosity (45)	Responses that didn’t specify any given activity but related to a way of being – such as inquisitive. Youth experiences which supported learning including freedom to explore
	Up Bringing Experiences
Family (86)	Family STEM background - taking family to museums- examples of formal science capital - typical of that most often quoted in relation to science capital Freedom or encouragement to explore in family outdoor trips Positive Dialogue during activity which promoted/ drew attention to learning

Considering the topical debate on the gendering of play and its impact on interest in science Table 8-6 shows the breakdown of these heuristic learning opportunities between male and females. The differences may be a measure of different interests and /or access due to stereotyping, as evidenced in the narrative provided by respondents and recorded here in quotes.

Table 8-6: Gender Ratio for Play and Pastime Pursuits

Heuristic Learning	% of total	%Male	% Female
Construction Toys	26	56	44
Electronics	13	84	16
Reading	15	54	46
Tinkering	10	50	50
Games	14	37	63
Pastime-Work	10	38	62
Sport	2	60	40
Computing	4	50	50
Musical Instrument	5	25	75

It was interesting to note the division of play. Construction toys had been almost evenly accessed by both boys and girls, however the narrative explains that the girls had access to 'boys toys' by virtue of having a brother or as the only child. Electronics was strongly male and a feature of the teenage years, ratio male: female 84:16.

With this predominance among males of hobbies such as Electronics and Sport, this gender bias is perhaps balanced for females who cite playing an instrument as a benefit to learning, male: female 25:75. Tinkering was evenly accessed by both genders, as was computing. Gaining useful physics learning through pastime work such as farm work, device maintenance and DIY was predominantly mentioned by females.

Items in this list could be considered most accessible to medium to high socio-economic background families with the exception of Tinkering and Pastime-work. It was an encouraging measure to find that both male and females equally explored and benefitted from Tinkering and that the learning from Pastime work was of benefit predominantly to females. Perhaps compensating for the limitation in physics related learning outcomes from 'girls toys'.

As a non-traditional sources of Science Capital, the Tinkering, Pastime Work, Sport and playing a Musical Instrument are important findings. Since not all young people have the opportunity to benefit from the traditional science capital*, it could be argued that the inclusion of non-traditional sources broadens access to physics learning for the underrepresented groups (females, low socio-economic, some ethnic minorities) by forming their physics perspective .

* Examples of traditional sources of science capital are immersion in science activity such as science museum trips, laboratory work experience and family employed in STEM careers.

Validation of these sources could yield the physics identity and sense of belonging that supports physics learning for these groups to be included in the future.

Respondents reported that the heuristic learning opportunities had enabled and enhanced their physics learning as follows:

- Creation of an interest in physics and a Physics Identity
- Realisation of the firsthand experience of physics phenomena such as forces, laws of motion, properties of light, electronics and electricity, to name a few.
- Development of spatial awareness, experimental techniques, investigation skills.
- Establishment of prior knowledge that had helped elucidate and consolidate physics understanding.
- Development the scientific approach of observation, fair testing, thinking and reasoning, problem solving and an analytical mind.
- Strengthening of mathematics by its use in physical context.
- Perseverance and mental focus
- Produce the confidence to question, debate, discuss, challenge and think aloud

Further descriptions of the activities and quotes are set out below.

Construction; 26% of responses reflected on play with construction toys. This may be a measure of the very high response levels of engineers in the population or that such toys. Lego, Knex, Meccano, are notable as learning toys -62% of the Construction replies referred to playing with either one, two or all three. It was interesting that these construction toys were described in gendered terms, and female respondents considered that they had benefited in having access to the boys' domain

> *I was not restricted to "gender-appropriate" toys.*
>
> *As a young girl, I had a trainset, toy cars etc. (as well as "traditionally toys for girls") which potentially developed special awareness and problem solving more than, say, dolls*.

However construction was not only related to building structures.

> *I used to construct guns, crossbows, catapults etc. from various building toys I think this helped to further my understanding of forces as I would attempt to improve the distance I was able to launch a projectile.*
>
> *I enjoyed knitting and sewing, both of which have mathematical/constructive aspects*

Sport: 2%

> *Playing various sports meant I had to react and interact with objects that changed throughout the game. This really helped me have an understanding of how the world around me worked. An example of this is learning to catch when playing cricket. Just this simple task in a sport I used to play a lot involved understanding gravity, air resistance and a bunch of other forces. Sports in general just really helped me understand how everything works and was something that I felt helped me do physics intuitively*
>
> *I loved active playing, e.g climbing trees and think that all this helped me understand the relevance of Physics.*
>
> *Playing outside with practical and physical games helped understand how things moved and the basics of forces.*

Work: 10%

> *Brought up on a farm so many problem solving and mechanical hands- on opportunities.*
>
> *My father and brother were engineers so we spent a lot of time designing and building things and finding out how they worked.*
>
> *I grew up on a farm with a father who was good at making things and repairing things, so I got to see machinery in pieces and observe how it worked from the inside. I also used to like taking toys apart to see how they worked.*

Electronics: 13% This category included Technology and Computing

> *I always had an interest in mechanics, electronics and space. Those interests helped with physics study as I tended to have an idea of the concepts being studied already. Instead most of the physics lessons were fleshing out my understanding.*
>
> *I had a big brother who was into all things technical and I was taken along to events with him and could play with his toys, so I had much more access than I would have been given in a gender defined traditional household*

Age related responses were noted under this code. Older respondents reported building radios, using valves and learning to program on early computers while the younger respondents referred to computer games, learning to program and modern technology.

Tinkering: 10% The term ‘taking apart’ or tinkering appeared often, including taking dolls apart and reassembling. Other related inventive play such as playing with ‘magnets and swings’ seemed to fit well with this group for the types of competences fostered.

> *Taking apart --Possibly helped with my problem solving skills, and being willing to take things apart in an attempt to fix them!*

> *I had a passion for finding out how things worked from early childhood. I dismantled my first doll before I was 5. (& put it back together again).*

Games 14% : Problem-solving through games (computer e.g. Repton games, board-games e.g. chess, strategy games, card games e.g. whist-based), computer programming for fun - taught logical thinking. .

> *Loved puzzles which helped with problem solving and logical thinking. I loved doing jigsaws and doing science feels a lot like jigsaws. When very young, I enjoyed jigsaws, which I think are good for developing observation and organising tasks.*
>
> *Tech--gaming - it supports logical problem solving*
>
> *I'm a huge fan of videogames, and would play them for hours. The mental focus and inventiveness videogames required really helped develop my abilities to work with such a logic-based subject*

Music 5%: Practising music and playing an instrument were mentioned as respondents felt this was akin to the learning that came from doing puzzles, pattern finding and a demonstration of the levels of perseverance perhaps needed to succeed with physics.

> *I am musical, clarinet and saxophone. I believe playing an instrument improves science ability and vice versa*

Reading 15%: Reading all types of books and science fiction as well as watching documentaries was distinct as a group. Perhaps because these are both self-explanatory, respondents did not elaborate on why they thought reading and watching documentaries were important in supporting their learning of physics. It is assumed therefore that such activities provided subject knowledge which could be drawn on as prior knowledge

> *I was also a huge fan of animal documentaries and science shows - for example, I adored the TV show Brainiac. I think this really cemented my love of science at a young age as well, and my love of the subject is what made me so enthusiastic about the subject. I feel enthusiasm is the best skill to bring to any interest or skill, as you'll always have the motivation.*

Upbringing Experiences

Under the theme of Family upbringing and Curiosity (34%), the responses fell into three categories; all of which could be considered to provide motivation to the learner. Internal motivation from the students' inquisitive disposition and external motivation in the form of positive encouragement that supported the ability to collaborate, ask questions, challenge, enquire, investigate and importantly socialise in a science environment. This equates to identification with physics and family science capital that normalised physics. Example responses and further specific analysis are set out below.

Curiosity/ Own Drive 22%: Respondents had found the resources within themselves and expressed the skills and competences that they nurtured

> *Given the opportunity to come up with crazy ideas. Heard stories of scientists working and having similar life stories to contend with (normalised science)*
>
> *Yes as a constructive day dreamer*
>
> *Generally being inquisitive about the world around me during my childhood*

Positive Feedback: **26%**

> *I don't believe physics ability has anything to do with your family background, but I do think that the encouragement and confidence required to allow capable children (particularly girls) like myself who come from working-class families and have no support network to help them imagine a career in physics is sadly lacking, both when I was at school and still today*
>
> *Parents' supportive approach while encouraging me to do as well as I could certainly helped me to develop a good approach to studying and perseverance*
>
> *Having no brothers - so my father gave encouragement which I suspect would have gone to a male sibling, had there been one.*

Family Science Capital:52% Many respondents wanted to explain how their parents and grandparents were scientists or engineers and how this was a benefit.

> *Social interactions helped me to have the confidence to discuss and debate concepts, ideas, and theories.*

Referring to Family Science Capital the breakdown of which family member/s were most engaged in encouraging STEM and scientific enquiry is shown below.

Grandfather	Father	Mother	Both Parents	Family	Brother	Extended Family
15%	38%	7%	20%	15%	3%	6%

Most respondents, identified with a male figure of influence or owner of the physics related activity. This male predominance may be a reflection of the dominance of males in physics and engineering. The stereotype view that physics is not a subject for girls is demonstrated in responses in the Minority category Section 8.1 and could play into who students look to for guidance or supportive interest in physics.

Female respondents pointed out how having a brother and access to 'boy toys' was an advantage or the absence of a son in the family meant that a father or grandfather focused the physics orientated activity towards them. Perhaps a function of the historic and male dominant status quo in physics and engineering careers.

> *I was one of two girls. My dad always instilled an attitude that there wasn't anything gendered about science or engineering. He was very practical and I would help him potter in the shed or garden. He trusted me & my sister to build the new kitchen flat pack. On reflection that trust gave us confidence in our capability. If either of us asked a "what happens if ..." question he'd encourage us to explore & experiment to find out*
>
> *My grandad and dad were engineers, although neither had degrees (HND instead). This meant a higher level of science capital at home comparably and exposure to "tinkering" with things and interest in things like steam engines and building radios etc. I was encouraged with a wide range of toys, ranging from imaginative play with dolls where I had a tendency to build them inventive vehicles, to being bought a tiny telescope and various science kits as well as a camera and learning basic image processing. Basically, lots of encouragement. Playing on the computer was an asset (early knowledge of excel etc.), girl guiding was too. Wide range of experiences.*

8.4 Physics Grounding and Careers

As set out in the introduction, physicists and physics qualified people are much sought after in a great range of careers (Powell and Snellman 2004) and the labour market demand exceeds supply . Examining what respondents considered influenced their choice to study physics, Figure 7-2, 59% identified a career in physics or engineering and 26% chose physics because it opened up many career opportunities. This 26% are an interesting group as physics is often held to be a passport to high level careers in academia, industry and business, with the range of sectors being wide and diverse - including non-physics careers (UKCES 2016). An American study (Bailey 2017) found that approximately 60% of physics graduates go to careers in the private sector of which 30% are jobs not directly related to physics.

Most university physics prospectus promotes these features of physics, indeed much is made of these features as recommendations for students to study physics. Examples of such promotion are *Why Chose Physics* (2019) and *Physics and Its Advantages* (2011a) .

However it is not only physics graduates who might have their career enhanced by having studied physics. This research sought to measure how having studied physics up to A level had impacted or supported the careers of the respondents who had not continued with physics to graduate level. Feedback was sought on how a ‘grounding in physics’ had helped their careers. These responses were produced as personal narratives and underwent phenomenographic analysis.

Physics Grounding

357 respondents, 54% of the total, completed Question 11c; *If your Physics Grounding has been useful in your career please explain how*. These respondents had not continued with their study of Physics post A Level, therefore the 357 responses made up 86% of the non-physicists respondents. As an optional question, this level of response is important since it would indicate that the term *physics grounding* resonated with respondents and they considered the way in which physics learning had supported and enhanced their career had merit and deserved to be credited in their response. The findings on grounding of physics were as follows:

Table 8-7: Usefulness of Physics Grounding during Careers

Usefulness of Physics to Careers	Percentage Response
Your physics grounding was helpful in your work	73.06%
Your physics grounding was very useful in your work	53.88%
Your physics grounding was NOT relevant to your career	10.50%

Note It appears that some respondents had selected both 'physics grounding was helpful' and 'physics grounding was very useful'. Of the 10.5% that reported that physics grounding was not relevant, besides the 9.44% of respondents that did not follow STEM careers only 1.06% reported that their physics grounding was not relevant to their career. A high proportion of almost 75% of respondents felt that their physics grounding was either helpful or very useful. By analysis two themes emerged on examination of the data:

Theme 1 Transferable Competences
Theme 2 Subject Related Competences

Table 8-8: Grounding Codes and Themes

Codes (n)	GROUNDING
Features of Physics Study - Transferable Competences	
Understanding (106)	Where the word 'concepts' had been used or the words 'principles' and 'fundamental'. Where the word Understanding was used or specific knowledge is outlined e.g. wave theory, in seismology by geologist ; radiation terms used by vets, forces terms used by podiatrists
Analytical (22)	Used the term analytical or similar
Logical (20)	Used the term logic or logical
Solving (40)	Mentioned problem solving or describe modelling
Rigour (49)	Mentioned of how physics developed a disciplined approach to work or scientific method approach, perseverance, methodical etc.

Acquired Subject Related Competences	
Eng. Chem. (117)	Most engineer and chemists responded to say – essential for/ fundamental to engineering and chemistry
Maths (21)	Any reference to competent use of mathematics.
Programming (12)	Respondent mentioned that they learnt to code or program through their physics education and their knowledge of physics helped them to program
Practical (26)	Reference to help with technical or practical work – most often used by technicians or design engineers

Some responses were extended statements with several codes. Examples of such multi code responses are given below with the codes shown in brackets after each statement or part of statement.

> *I understand science to a high level and have the ability and confidence to work out new concepts quickly. This is a result of my physics grounding. I use this as the basis of my communication (Understanding). Physics is an increasingly needed skill in the life sciences as in the development of models(Modelling), I find my knowledge of physics gives me an insight which is often lacking in the life sciences because it is more common to come to these through a chemistry-biology route.*
>
> *Thinking of problems in a mechanistic way (Solving, Rigour), Maths skills (Maths) , understanding physical laws (Understanding) helps underpin what is happening at chemical and biological levels of organisation.*
>
> *At the very least it was methodical, working out different ways to approach a problem, as well as questioning (Rigour). It gave me more opportunities as often I would be more numerate (Maths) than others in the same office.*
>
> *The contribution that physics played as the building block to my degree cannot be understated. My degree is vocational and my current level of seniority, experience and salary is a direct result of the cumulative learning about physical principles (Understanding) and real world applications (along with professional competencies) that I have developed from school (Rigour).*
>
> *Being able to communicate effectively with other scientists and engineers. Thoroughness. Patience to find solutions. Team work all important and developed as I studied physics (Rigour)*

Theme 1 covered the features of Physics as the *Transferable Competences*. These included: *Understanding of fundamental principles, concepts and axioms* which could be drawn on, in so many instances, in so many disciplines.

Respondents also referred to their use of *Key Knowledge* that they applied to situations in other 'non-physics' disciplines and their acquired *Logical and Analytical Reasoning*.

Many felt that a Physics Grounding set them apart in their ability to *Problem Solve* and demonstrate *Creativity in Modelling* situations. Overall they appreciated that through their physics learning they had established a scientific *Rigour* as a way of working. Applying the scientific method and performance strategy to any task. This was conveyed in terms and statements such as:

> *The patience to find a solution*. *The ability to facilitate discussion and cooperation between researchers in the field. The ability to understand that most things in life can either be described in systematic terms or actually are constructed on systematic principles.*

From the structures around physics and physics investigation, respondents noticed that they had developed *Logic* and *Learning how to learn*. They noted that their approach was *Methodical* and demonstrated *Perseverance* as defined here in the *Rigour* code.

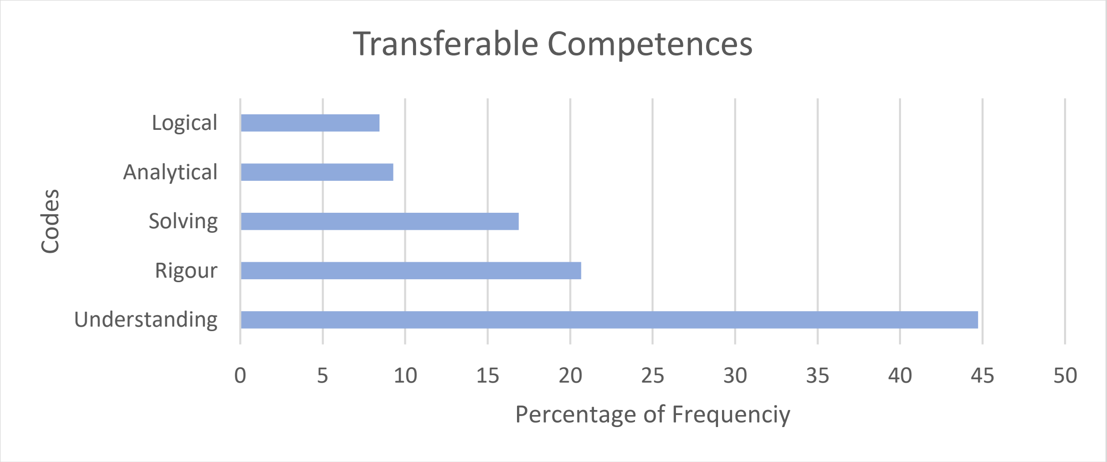

Figure 8-2: Transferable Competences acquired through Doing Physics

Theme 2 was the *Acquired Subject Related Competences.* 66.5% of these responses were from those who had studied *Engineering or Chemistry* degrees and considered that their study of physics had been important in their understanding of chemistry and engineering. Others referred to sets of practical and technical competences acquired. These respondents referred to technician type roles such as laboratory assistants in schools and industry and those involved in science communication such as STEM Ambassadors who were involved in developing hands-on activities for outreach work.

The *Mathematics* code encompassed those who had acquired mathematics skills and knowledge through the study of physics or felt their mathematics competence was enhanced by the context of physics.

Others had learnt *Computer Programming* solely through studying physics and had therefore had a new career pathway opened to them, or stated that their physics grounding supported and enhanced their programming skills and the modelling aspects therein.

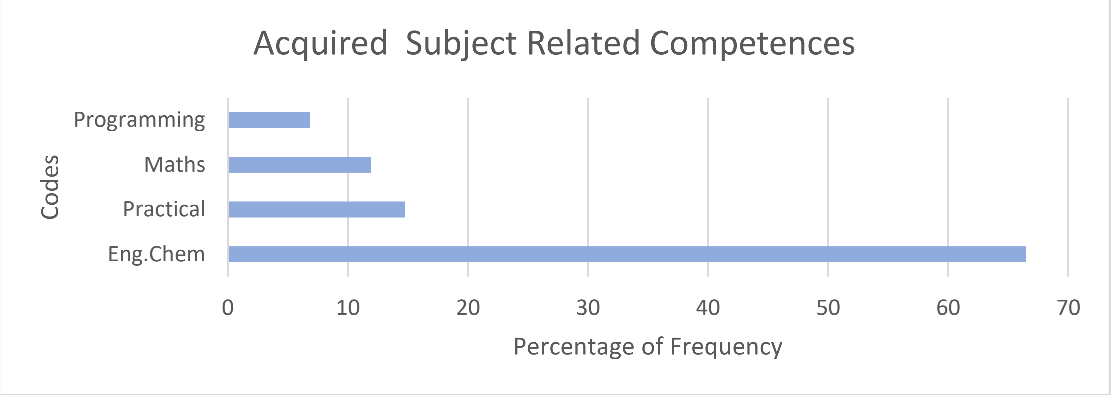

Figure 8-3: Subject Competences Acquired through Doing Physics

8.5 Summary – Phenomenographic Analysis

This was a phenomenographic analysis of the narrative responses. By an iterative and comparative process, categories of descriptions emerged which equate to emic descriptions - 'experience-near' concepts - that describe the meaning of the respondents experiences of learning.

Physics study is skewed to benefit an advantaged population, with other groups under-represented. Although this research did not directly investigate the socioeconomic background of respondents, such information did come across in narrative questions and the ethnic spread was representative of that in physics. The hypothesis however was that the population that did make it through the obstacles and barriers to physics would still have experienced or noticed the barriers and their impact on other students who belonged to the underrepresented groups.

It is in their narration that a measure of these factors could be obtained such that they could be addressed and so allow access for the underrepresented: social, ethnic, educationally disadvantaged and by gender.

The most disadvantaged group was females in physics, and metrics were produced on the severity of the problem. Barriers to their learning were identified and pointed towards solutions in the practices, culture and policies in schools which could be addressed.

Examining the hypothesis that childhood and teenage informal out of school activity; play, hobbies and family upbringing enabled and enhanced physics learning was borne out in the results.

Respondents recognised the physics learning and its importance in initiating, consolidating and embedding of physics knowledge and competences. The metrics that were calculated, verified the level of importance that should be attributed to this input, with particular importance to validating the non-traditional learning resources of the under-represented groups.

Acknowledging and drawing focus to these factors was part of the ethos of this study, to provide a positive and inclusive narrative in doing physics – by which female students and those from lower socioeconomic and ethnic backgrounds may better see their place in the physics classroom.

With regards to the impact of physics grounding on career success, 86% of the non-Physicists respondents provided narratives. This high level of response to an optional question reflects the strength of feeling that respondents felt, that credit should be given to learning physics in a holistic assessment of the subject.

Feedback fell into two themes, Transferable Competences and Subject Related Competences. The Transferable Competences which were reported to enhance the respondents' ability to perform well in their chosen non-physics career included: Cognitive Competences acquired or honed through doing physics, Key Physics Knowledge that proved useful in a cross discipline application, Work Strategies pertaining to the scientific method, perseverance and a developed uncertainty orientation. Subject Related Competences were acquired as a result of doing physics such as learning a programming language and physics concepts that were part of engineering, mathematics and chemistry.

Chapter 9 : Conclusion

This chapter summarises the

- Context Created from the Data Collection
- Findings and Outcomes
- Conclusions
- Limitations of the Study
- Future Work

The prevailing and current status of low uptake of physics study post 16 years and the demands of the knowledge economy and technology advancement, supports the strong argument for encouraging more school pupils to study physics up to A level and then recruitment on to STEM degree courses. Recruitment studies also show the value of studying physics up to advanced level for those who do not follow any graduate or STEM route, because not only is physics knowledge important but also the capabilities and capacity developed by physics learners are sought by employers.

Therefore this research compiled and explored a set of Physics Competences, Physics Learning Competences and Physics Identity to produce outcomes that are relevant to the future of physics education. To this end, the aim was to achieve a deeper understanding of the demands of doing physics and to establish if a threshold exists to becoming a sustained physic learner. This was successful.

Considering the possibility of guiding future pedagogical change and new theories of practice, this study has examined the components of Physics Competences and the Physics Learner’s Competences and their relationship with successful study.

Assessing the mastery of these competences and their indicators for a large population of respondents has created a measure of what makes a physicist and the diversity of success in physics learners, rather than a fixed threshold. Considering the future work described here, this measure of the physicist and what success in physics entails, could provide a means by which young people, parents and their teachers, can see how the student fits the physics learner spectrum, therefore creating a powerful positive and inclusive narrative in physics learning.

9.1 Context Created from the Data Collection

This research study met its aim, to reach a target sample of physics educated people by gathering responses from a sample of 657 people, in the age range 18-75+years, equivalent to six decades of secondary level physics student education. The respondent population members were wholly representative of the geographical population spread of the UK and of the current population demographics of physics at secondary school level and university level, with the traditional inherent biases and skew evident. This bias and skew is a demographic weighted in favour of independent schools 24%, grammar school 30% and state maintained schools, which were possibly the more academic state schools, 45%. In the case of females, 17% attended all girls schools and for those who went on to study physics at university 63% had attended all girls schools. In more recent years students entering for A level physics have been required predominantly to have achieved grade A at GCSE level physics and hence an academic elite from predominantly favourable education environments as shown in this study.

Females make up only ~ 21% of students at A Level and as undergraduates, however 51.7% of respondents in this research were female, therefore giving equal voice to females and males. Although this may be considered to be an over representation of females and therefore a limitation of the study, this level of response was very important when analysing the gendered differences. This was especially important in relation to the challenges faced by females as a gendered minority in physics classes, where 37% of all female physics learners were negatively impacted by their minority status. Considering that females who study physics may be considered to be an academic elite (Archer *et al.* 2017) the fact that they still experienced negative impact on their learning is an important finding. It could be extrapolated that as this academic elite are challenged (not in their academic learning) in the learning environment then other females may be finding the level of this challenge insurmountable to continue with their study of physics; in this way the 37% measure accounts in some way to the ~30% of females missing from physics education at secondary and tertiary level education. Possibly because these impacts experienced by the female minority had been barriers instead of challenges for those potential students who opted out of physics.

The research concluded with a number of findings, outcomes and suggested directions for future work as set out below.

9.2 Outcomes and Findings

The dataset produced by this research was extensive: 657 respondents have created data for 69 Learning Profile Indicators, 46 Physics Competence Indicators, 54 Indicator linked options on Learning Competences, Physics Identity and Learning Characteristics which included Motivation and Self-assessments of Ability. 36 codes were derived from narrative responses on Enabling Physics Learning and Physics Grounding. Hence a 657 X 205 matrix yielding 134,685 data points has been generated.

A set of five Physics Competences were identified and compiled as: Representation, Experimental Investigation, Problem Solving, Thinking + Reasoning and Modelling. These five Physics Competences were distilled to yield a set of variables of doing physics. Employing the characteristics of Advanced Cognitive Performance and recognising the components of Cognitive and Procedural Competences, allowed the author to produce 46 Indicators to fully describe the competences. These Indicators are a means of conveying the content and extent of all aspects of physics learning across all fields of physics, making them accessible to all stakeholders; from schools to universities, employers and policy makers as well as to any interested layperson.

A four point, non-linear scale of mastery was devised for the Physics Competences. Correlation analysis of the scale with the physics A level grade attainment allowed the scale to be evaluated. It was found to discriminate between two grade attainment ranges A*AB and C-F. It identified the physics learning challenges for students at both attainment ranges for each competence. Thus the Physics Competences were ranked in order of challenge from Representation to Experimental Investigation, Problem Solving, Thinking + Reasoning and Modelling.

A marked difference in the high level of mastery of the Representation competence among the A* A,B grade cohort of high achieving student respondents may provide them an advantage across all other competences. This could be a possible argument for further work on developing the Representation competence in the evolving physicist and certainly supporting the students similar to the C-F grade cohort studied here, to develop the Representation competences.

Statistical analysis on the 46 indicators of Physics Competences allowed them also to be ranked for levels of ease and challenge in mastery. Therefore there is the potential that this ranking of indicators could act as a guide for curriculum development and pedagogy.

A pairwise correlation analysis of the indicators showed that the level of correlation between Indicators within the three competences, Problem Solving, Thinking+ Reasoning, Modelling, increased in this order, such that the highest correlated Indicator pairs are within Thinking + Reasoning and Modelling.

Few indicators showed cross competence correlation and these few were in the higher cognitive competences of Problem Solving, Thinking + Reasoning and Modelling.

Representation and Experimental Investigation were shown to be generic and in most parts procedural competences. While the other Competences had greater elements of cognitive competence.

Adapting a mathematical method to average the response per indicator, per respondent, for the total population showed that for each Physics Competence, a bell shaped distribution outline was evident. Summing these sets of averages for all Competences created a continuous bell shaped distribution in the range of 1 to 4 units, as a calibrated Mastery Scale. As an outcome this scale shows the diversity of mastery of physics competences of those who have succeeded in physics up to at least A level standard. This bell distribution therefore shows that there is not a fixed threshold of success but rather a spectrum.

A percentage frequency analysis of the dataset for the 69 Indicators which encompassed Learning Competences, Learning Characteristics and Physics Identity produced a Learning Profile typical of a large population of STEM educated respondents. This Learning Profile indicates which, and how much, of the profile indicators are needed to nurture interest and sustain the physics learner.

Examining how physics is important to a wide range of STEM and non-STEM careers, the research explored respondents' views on how a 'grounding in physics ' had supported their careers. This confirmed that the learning of physics brought about two career advantages. First were the transferable competences acquired or honed during the process of doing physics: logical and analytical thinking, problem solving abilities, creativity, rigour and performance strategies, confidence in questioning, debate and discourse. Secondly new subject competences were acquired through doing physics. These were better understanding of the fundamental principles of engineering and chemistry, acquired mathematics skills, computer programming and technical or practical skills.

9.3 Conclusions

This research study has defined Physics Competences and Learning Competences for physics learners and a means of scale which could be very important in developing a competency based physics education infrastructure. Jones and Voorhees (2002) suggest that a competency based physics education aligns well with the outcomes of two decades of physics education research. It offers a solution to the recognised need for change of the traditional education delivery, to one that takes account of the knowledge based modern economy. With advances in information technology, knowledge will continue to grow and learning pathways can be expanded. Concentrating on developing competences makes management of knowledge growth and adapting to new challenges and the new careers possible for a greater number and diversity of people, and this is much needed in physics to counter the low uptake.

It could be concluded that the set of Physics Competences and associated Learning Competences assembled and synthesised in this study, drawn from and tested by a large sample population of successful physics learners in physics, have been proven to enable or resonate with physics learning. Therefore they form a foundation for any competency based pedagogy.

During the Covid 19 pandemic of 2020-2021 the use of technology aided delivery at school and university level and its associated changes to pedagogy may have initiated and progressed new approaches in Technology Enhanced Learning. Such development is a step closer to introduction of personalised learning modes and therefore development of competency based learning becomes increasingly important.

Analysis of the Competences and their Indicators showed that differences in mastery could be evaluated. It was possible to rank the indicators for levels of ease of mastery and the correlation analysis showed that certain Indicators were independent and generic while others were interdependent. This has implications for improved pedagogy as the interdependent Indicators may yield better learning outcomes if considered as a group or groups. Where some specific features were noted among sets of Indicators, for example among the Representation Competence, then further analysis has been indicated. Use of Principal Component Analysis may regroup the Indicators to map to different Physics Competences and this could aid teaching and learning. The distinct difference in reported mastery for Representation between the groups with higher and lower grade achieved at A level may provide direction for pedagogy in this area. Providing more support, time or emphasis on the importance to master Representation may have benefits for learning in all other competences.

The Learning Profile along with the response to the Physics Competences and the Mastery Scale showed and quantified the diversity of success in physics. In the case of mastery of Physics Competences, this diversity was described as a continuous spectrum, and not a fixed threshold. This truer picture of what success looks like could be used to encourage a more diverse uptake in physics and a reconsideration on entry qualification to the subject by public exam grade attainment alone.

With regards to academic attainment at A level, it was found that those who described themselves as Blue Sky Thinkers, Natural Physicists and Gifted Physics students, did not all have the top grades of A and B and in fact attainment spread across the full grade range as shown in Table 7-7. Since such respondents, who might be regarded as ideal physicists, had in some cases achieved low grades at A Level yet academic and career success later, this merits further investigation. The current selection criteria at A Level and university level are based largely on achieving the highest academic grades, therefore excluding such potential candidates.

The set of Physics Competences along with the Mastery Scale have the potential to be a student self-assessment tool for success in physics. Differences were identified between those who went on to become physicists compared to STEM graduates.

These mastered competences would be a good means to direct schools students to further physics study. In addition, with such self-assessment, students would see on the scale of mastery of physics, where they fall within the range of those who have succeeded in physics qualification at A level, then succeeding in further study of their choice and who have been successful in a diverse range of STEM and non-STEM careers. This is both a positive message of encouragement and also a means of identifying where more specific work or support is needed.

Considering that the set of respondents were almost all graduate level educated, it could be said that they belong to a band of higher intellectual ability, yet ~30% of each STEM and non-STEM degree category respondents, acknowledged the need to work hard to understand physics. This is not to say that 'physics is hard' but the subject challenges the learner to 'work hard' to bring to bear multiple competences to achieve deep learning. With regards to encouraging more young people to continue to study physics, this finding should be reported as reassurance that needing to work hard is not a problem or indication that the student is not an able physicist. This suggests that a positive step to improve uptake would be to change the narrative on physics, away from 'Physics is hard' to the more positive narrative that physics requires, and trains, the learner to achieve depth of learning and focus.

Significant gender differences were found between how male and female respondents described their student-self for both the Learning Profile and Physics Competences. Among all respondents, females had on average achieved the better GCSE/O and A Level grades and those who had become physicists had the same levels of physics qualifications at degree and post degree as their male peers, however males described themselves more often in traditional physics expressions relating to the Physics Competences, such as: inventive, found physics intuitive, good at building mental models, good at abstract thought and hence a stronger and recognisable physics identity. Females more often described themselves in terms of work strategies, Learning Competences and Learning Characteristics, such as: conscientious, hardworking and persistent. This suggests that consideration should be given to the narrative around what makes a physicist to be inclusive of the descriptors preferred by females. In this way it could be concluded that to encourage more females to study physics the narrative around who is suited to be a physicist needs to change to include this female physics identity.

Although there are many studies on the correlation between certain challenging factors and uptake in physics, this study was important in that it established metrics for the size of the various impacting challenges. Of particular importance is the extent of negative impact arising due to gender on the small population of females who had studied physics. 37% of this cohort considered that their learning had been hindered in a number of ways which was not the case for their male counterparts. The most negative impact factors related to the school environment, which could be appropriately addressed to improve the learning experience of physics students and girls in particular. These include; addressing the stereotypical and negative references to girls' ability in physics, providing a more supportive environment in the classroom for girls where the number of girls may be as low as one, provision of peer support and validation of female students' contribution to the physics class. Other school changes could address the barriers for both males and females to entry at sixth form level by taking a broader and more inclusive view of who belongs to the physics class. For students who do not wish to study mathematics at A Level, there is indication that additional support is required to make up the deficit in learning of necessary mathematics knowledge and skills.

Students also would benefit from encouragement and practical support to deal with the step up in cognitive demand and workload from GCSE to A Level.

The positive experiences and learning opportunities beyond the classroom that were part of: childhood upbringing, play, hobbies and pastime-work were felt by respondents to have enabled and improved their ability to understand and learn physics. This is important as it gives valued recognition to some non-traditional sources of prior physics knowledge, by which students from lower socioeconomic and ethnic backgrounds and females are to see their place in the physics classroom. In particular that of pastime work as a source of prior physics learning since students of low socioeconomic backgrounds or certain cultures, and girls, would not have access to the more usual described Science Capital. Instead such students may be required to work to support their families or contribute to the family household workload, this research confirmed that in doing so they do acquire physics prior knowledge and consolidation of physics learning. In the case of girls, some may only have access to physics enhancing activity through certain types of pastime work, and not through female focused play and hobbies which are not so well linked to physics. Value should therefore be placed on this significant contribution which induces an interest and gives recognisable experience in physics, that enables and consolidates subject learning.

9.4 Limitations

There were limitations to this study which could be addressed in any future work of its kind. These limitations were identified as:

Females made up 51.7% of respondents even though only ~ 21% of physics A level and undergraduate students are female. Although this statistics gave equal voice to females and males, that this voice may be predominantly that of the 'exceptional physics girl' (Archer. L *et al.* 2017) is a limitation in the study. However it was shown that the female respondents still incurred the negative impact already well documented for under-represented girls. The challenges experienced by this group of females may equate to the barriers experienced by those girls who do not continue to study physics. Importantly the metric of 37% of female respondents experiencing negative impact to their studies confirms the gravitas of the problem.

The study was Anglo-centric, although it did represent each UK nation accurately by percentage population distribution.

Data was collected as a single-shot approach with no follow-up for any respondents or groups of respondents. This may have been limiting for the narrative answers, as further discussion with respondents may have eased and fine-tuned the coding process as well as providing triangulation to enhance validations.

Respondents were predominantly high achieving STEM graduates and few came from apprentice or technician routes.

Respondents were accessed through STEM stakeholder portals and not by open and general public entry. However the use of social media portals may have allowed a wider pool of respondents to respond.

9.5 Future work

The database created by this research, 657 X 205 matrix yielding 134,685 data points, has potential for further analysis. This proposed analysis could be the next stage development of the findings and outcomes as summarised in new analyses by different statistical methods than used here (New Statistical Analysis) Section 9.5.1 or extension of the analysis for undergraduates (Extended Analysis) Section 9.5.2

This proposed future work would be important since the outcomes of this research are timely for new approaches in learning. Twenty-first century teaching methods now attend to the cognitive and motivational state of the learner, as addressed here under Learning Competences. Since a new era of Technology Enhanced Learning is evolving, deep learning, cognitive modeling and technology can converge. (Kim and Hannafin 2011). This will bring about a new type of student centered learning. Amy Ogan (2017) debates this student centred/led approach as she refers to the work of Johnson (2015) and Roll et al. (2011) in her online article, Precision and Personalised Learning, in which she states *"No longer a "one-size-fits-all" approach in which everyone in a class sees the same material at the same time".*

Students working online will give rise to personalised data and learning footprints such that pupils and students could be enabled to assess their own learning needs. In addition to the role of the teacher, if students, presented with a competency based learning option of the exact competences needed to succeed at physics will allow them to develop strategies and measures to put in place for their personalised precision learning. In addition courses that are open access will enable greater uptake by a more diverse population of learners.

9.5.1 New Statistical Analysis

Three further analysis methods that may prove useful for the next stage use of this large dataset have been identified.

- Principle Component Analysis may be a suitable approach to find the key determinants in succeeding in physics and in the re mapping of the Indicators onto the Physics Competences as discussed in Section 5.4.

- Huber and Seidel (2018) present a novel methodology for analysis by using the Shannon-Weiner Diversity Index which they adapted from its use in diversity measures in theoretical biology. They used it to analyse the interplay between the characteristics which influences physics learning for three students and compared this to their teacher' assessment of their learning. There is scope for application to this data set.
- Eric Brewe (2018) in his review promotes the use of Network Analysis as relevant to Physics Education Research. As well as Principal Component Analysis

9.5.2 Extended Analysis

It is envisaged that the 46 indicators and the Mastery Scale could be used to assess physics competences for undergraduates and have the potential to be used to target pedagogy and curriculum development and hence the analysis could be extended in this regard.

The Mastery Scale could be adapted into a self-assessment exercise for success in physics. The aim being that students would see that on the scale of mastery of physics, they may fall within the range of those who have succeeded in gaining a physics qualification at A level and then succeeding in further study of their choice, and be successful in a diverse range of STEM and non-STEM careers. Extension work could review the data presented here and other data collected to relate to self-assessment and career choice.

The Learning Profile, created as a compilation of responses from a physics educated adult population, could be adapted to a secondary school level. The resultant student Learning Profile could be used by school groups as an assessment of a student's aptitude and ability to study physics. Since the Learning Profile in this study shows considerable diversity it may be the case that a greater number of students are encouraged to take up physics as they see they fit the profile of a potential physicist.

Appendix A Personal Perspective on the Research Study

This research in borne out of a personal interest in challenging these, now traditional situations of under representation of female and other groups-students from some ethnicities and lower socio-economic status- in physics. I am one of that small minority who has succeeded at physics and in physics related careers even though I had belonged to all the ’disadvantaged’ categories referred to in Section 1.1. *Therefore I am interested in what it is that carries us through the journey of learning and enjoying physics so that we can set down road signs for others to follow.*

My approach to the research was influenced in the first instance by my opinion, and long term experience in education, that those young people who succeed have, at some point, worked out their strategies for learning and adopted hardworking, conscientious student behaviours. It would appear that such learning behaviours are particularly critical to learning physics. It may be for physics study that a high level of performance in this regard is needed to get the necessary foot hold on the subject. With this ability to learn, with one’s own personal strategy for learning developed, it is then possible for a student to enjoy the subject and succeed to overcome any other challenge.

I believe that the advantages of a high Science Capital and Physics Positive Cultural Capital that currently works for the few, can be matched among all other young people who may not have access to, or engagement with, these conventional science/physics enablers but have developed skillsets and competencies of a comparable nature. Recognition of these other competencies and their transferal or adjustment into recognised educational learning strategies would be a positive approach to improving learning in many disciplines for such students, and this research highlights how this might be achieved for physics. So it is my belief that success and enjoyment in studying physics requires certain learning behaviours which support in depth study, learning strategies and specific cognitive and procedural competencies that the student must master. In this way the student can work and behave in a way that resonates with the learning and acquisition of physics knowledge. Were this all possible, this creates success and reward for effort and most important a sense of achievement and rise in status as a physics learner.

First of all for physics we need to be clear what these competences are; in essence the basis and direction of this research. The intended direction was to find what might be the threshold competences and at what level they are needed to study physics so that these may be put in place to support the learning of physics with a larger sector of the school population. For the learner this means developing the necessary set of competencies and also adjusting their personal paradigm to encapsulate the values, attitudes and beliefs to cross the ‘doing physics’ threshold.

This is my position and these views, personal experience and opinions have influenced and shaped the aims and direction of this study and the research questions that have arose from them. However my position will not bear any influence on the data collected as explained in the following.

Given that the general view in the UK is that physics is a ‘hard subject’ and only few are able to understand it sufficiently, it seemed apposite that my initial research in academic literature should be into the capabilities of high achievers, intelligence and into physics education research itself.

I have found that there is much longstanding and very rich educational research into giftedness, theories of learning, intelligence, teaching and learning of science and some direct research on the learning of physics. Also there is research into attitudes to science, attitudes to science careers and understanding of science. Therefore my views, opinions and personal theories can be replaced by the years of quality research by eminent researchers that can be used to guide the exact form of the data collection and remove any bias/ reflexivity that may have otherwise persisted in the study.

Looking thus at the learning and understanding of physics and its epistemologies, is central to this research project. The aim is to understand and classify the learning factors and competencies for physics. In the long term this may appear as a ‘success strategy’ for learning physics.

Appendix B Questionnaire

Background and Consent

Many believe that 'Physics is Hard' but You Succeeded! Please complete this questionnaire to share your experience of learning and 'doing physics' and to highlight the extent to which you employed different competences. Our aim is to collate your responses with all others and draw from these collective results some *Learning Factors* that could help the future generations of school students to recognise their potential to study physics.

The questionnaire is targeted at anyone who has at least one qualification in physics post 16 yrs. (e.g. A Level) irrespective of their route of study or career beyond that. There are no questions requiring any specific physics subject knowledge.

This research is sponsored by The Ogden Trust - a charitable trust which promotes the teaching and learning of physics.

Participant Information

1. **Consent** : This questionnaire is carried out in accordance with the regulations of the Mathematics, Physical Sciences and Engineering joint Faculty Research Ethics Committee : Leeds University: Ref MEEC 17-024 . It complies with the General Data Protection Regulations GDPR 2018.

Record of Learning History and Career

This questionnaire is anonymous, but to allow us to return to your questionnaire should you request us to, we ask you to create your own code. This also gives us some demographic information to check the patterns by region.

2 Create a unique code consisting of:

Number of Letters in your First Name/ Month of Birth/ Town or City of Secondary School/ Country of Secondary School.

Number of letters in First Name: Month of Birth: Town or City of Secondary School:
Country of Secondary School

2. a - Country of secondary school: England Scotland N. Ireland Wales Other

2.a.i. If you ticked 'other' please specify

3. Age range
18-22 23-27 28-35 36-45 46-55 56-65 66-75 76+

4. Gender:: Female Male Other Prefer not to say

5. Define your Ethnicity - Using the UK Government definition of Ethnicity http://www.ethnicity-facts-figures.service.gov.uk/ethnicity-in-the-uk
White Black Asian Mixed/Multiple

6 What type of school did you attend from the age of 11-18yrs. Tick ALL which apply to you.

Further Education College, Co-Education, Single Gender Grammar, Independent/Public, Comprehensive, Home Schooled.

7. What Physics qualifications did you gain at school, typically at age 16yrs? If different from those listed, select the most similar qualification.
O Level Physics CSE Physics
GCSE Single Subject Physics/ Scottish Standard Grade/Irish Junior Cert GCSE Double Award Science
BTEC Science
NVQ - Physics modules

7.a. Exam Grade at 16yrs

8. What Physics qualifications did you gain at school, typically at 18yrs? If different from those listed, tick the most similar qualification.
A Level Physics, Baccalaureate, Scottish Highers, Irish Leaving Certificate

8.a. Exam Grades at 18yrs

If you did not continue to study or work in physics beyond age 18yrs, please move onto Q10 and complete the rest of the questions as we ***value*** and ***need*** your responses to compare your experience and relationship with physics to those who did continue.

9. If you have physics qualifications gained beyond school, please record these below. If you are currently studying choose two options - 'Current Student' and the qualification you are studying for. If your qualification is different from all listed, tick the qualification which is similar.

HND/Diploma University Degree MSc/MPhil/MA/MDA/PGCE PhD Current Student

10. If you did not study Physics beyond age 18yrs, what were your reasons for stopping?

10.a. If you took a higher qualification in another subject then please specify e.g. BSc Chemistry, BA History/ French etc.

11. Please identify your career path below. If you have had a varied career please tick all relevant options.

	Career/s
University Physics	
Physics R+D	
Physics Teacher	
Engineering /Technology /Manufacturing	
Computing/Mathematics/Finance	
Medicine + Health	
Science + Science Related	
Non- Scientific	
Still Studying	

11.a. Please feel free to say more about your career.

11.b. Was your physics qualification, subject knowledge, general grounding in physics of use in your career? Choose any relevant options.

	select
Your physics knowledge was essential to your career	
Your physics knowledge was essential in early career before	
Your physics grounding was very useful to your career.	
Having a physics qualification helped you get a job	
Your physics grounding was not relevant to your career	

11.c. If your physics grounding has been helpful in your work, please explain how.

Building Your Learning Profile

12. With ***hindsight*** how would you now describe yourself as a physics/science student at secondary school: From the list below please **choose *ALL* statements** which best describe **the type of student you were**. The characteristics are purposely listed in a random order and you should **choose without much deliberation.**

You loved physics
Physics was ok as a subject and you could do it
You really didn't like physics but knew it was an important subject you would need
You had to work hard to understand physics
You had an inherent talent for physics
Others viewed you as a definite scientist/engineer
Curious/inquisitive
Liked a challenge
Tenacious
You were inspired or enthused by a role model
Conscientious
Quick minded
Good at abstract thought
Liked science experiments
A good head for facts
Quick recall of relevant knowledge
Patient and persistent in your studies
Saw yourself as a physics person
Academic / geek / nerdy
Recognised yourself as a future scientist, physicist or engineer
Loved to study
Aware of your learning - had learning and studying strategies
Determined to see a task through to the end
A problem solver
Methodical
Inventive
Able to spot your own errors

Liked to be rated as clever
Systematic - you liked to create order and produce diagrams, tables etc.
Liked to see the big picture
Could work independently
Quietly confident in your abilities
Enjoyed working with mathematics
Able to present your ideas clearly and accurately
Enjoyed building mental models - seeing with your mind's eye
Liked the iterative nature of building understanding
Resilient to set backs such as getting the answer wrong
Believed in practice makes perfect
Sometimes or often solved questions differently to others - innovative
Enterprising - thinking differently and striving to improve
Resourceful - you would find a way to do what it takes - can do attitude
You were an ideas' person, reflecting and playing with ideas
Logical
Not put off by complex or ambiguous concepts and questions
Achievement motivated
You learnt from your mistakes
Took great pride in your physics knowledge
Loved working with equations and formulae
Got a buzz out of physics
It was important that through physics we could make the world a better place
Worked quickly through calculations
Had a feel for numbers
Liked how physics explained so much of everyday life
Liked talking physics/mathematics/ engineering
Compared to others you could do a number of stages of a problem in your head
Knew when you were on the right tracks
Liked the accurate use of language in physics - the scientific terms and formulae
Could usually come up with new idea to solve a problem
Enjoyed expanding ideas when getting to grips with a new topic
Good at recognising links in information, experiments and data
Good at recognising patterns in information/numbers/observations etc.
Observant - you had an eye for detail
Hard working - put in the effort
You found physics intuitive –understanding phenomena came with ease
You liked to help others with understanding physics
Key knowledge came to mind unconsciously
Often used your initiative in lab work and problem solving
You were good at Mathematics
You were good at English

Doing and Mastering Physics

Whether you found physics intuitive, developed a strategy for learning, or worked on a need to learn basis, please describe your '"doing physics" experience in this section to allow us to map the diversity and range of process. Please Note: These questions are still reflective on your physics study and experience up to age 18yrs ***so that all participants can respond***. Please attempt to give an answer for each statement in Q13-17 below. Tick one box per row that is the ***best estimation of how well you could do each***.

13. Communication of Physics

With Ease / With typical level of Effort / With some Guidance / Challenging	Ease	Effort	Guidance	Challenge
Use technical and scientific language				
Work with approximation, orders of magnitude, rates, proportion, exponentials etc.				
Define phenomena in relevant physics terms				
Apply scientific method and conventions				
Search for and understand information about concepts.				
Understand and explain phenomena represented as a diagrams, graphs, tables or in a mathematical form				
Communicate data and physics concepts as diagrams, graphs, tables or in a mathematical form				

14. Experimental Investigation

With Ease / With typical level of Effort / With some Guidance / Challenging	Ease	Effort	Guidance	Challenge
Identify phenomenon or physical properties involved				
Determine a set of variables to control				
Modify and adapt standard methods and procedures to detect, identify and quantify				
Accurately observe and measure				
Determine the reliability and plausibility of results				
Analyse and Interpret data				
Develop and refine conclusions				
Understand the relationship between theory and experiment- i.e. design experiments from theory or apply physics theory to experiments				

15. Problem Solving

With Ease / With typical level of Effort / With some Guidance / Challenging	Ease	Effort	Guidance	Challenge
Distil a problem to its basic elements				
Break down abstract and complex problems into multiple stages				
Ask relevant questions, identify patterns, relationships				
Create new ways of framing a problem or phenomenon				
Explain abstract, theoretical situations or models				
Translate a narrative into mathematical form				
Apply geometrics and algebraic proofs				
Explore alternative ideas or solutions to problems				
Combine or rework equations to suit new situations and context				

16. Reasoning and Thinking Skills

With Ease / With typical level of Effort / With some Guidance / Challenging	Ease	Effort	Guidance	Challenge
Understand the nature of physics - its axioms, theories, principles and conventions				
Draw on prior knowledge relevant to the task or phenomenon				
Interconnect prior and new knowledge				
Take any statement about the individual object or event and generalise.				
Imagine the object or event in ' ideal' conditions				
Apply probabilistic reasoning				
Apply known principles to complex, imagined or theoretical situations				
Develop compelling ideas and hypotheses				
Deduce - reason from a general principle to a special case				
Induce - reason from a number of special cases to a general principle				
Defend your ideas /premise by constructing logical arguments				

17. Physics Models

With Ease / With typical level of Effort / With some Guidance / Challenging	Ease	Effort	Guidance	Challenge
Distil complex and abstract phenomena to get to a set of parameters and relationships				
Produce a mental representation or conceptual model -thought experiments				
Visualisation of data - mentally organise and process				
Interpret prior learning and experience for new situations				
Use logic to deduce a relationship				
Come up with relevant original ideas for explaining, measuring, predicting				
Develop descriptive models to understand complex systems				
Create a mathematical model that describes the phenomenon or problem				
Interpret and contextualise mathematical descriptions of physical phenomena				
Use constituent parts to predict behaviour				
Combine the process of evaluation and adaptation to observations, reasoning, induction, deduction modelling, prediction and testing				

What Else Does it Take to Succeed with Physics?

18. In addition to the physics processes on the previous page, there are also varied learning behaviours and attributes. Select from the list below ALL that apply to you.

You were competitive i.e. liked to score high in homework and tests.
Aware of your strengths and weaknesses and adapted accordingly to improve performance
You would check back, re- evaluate and re-work your notes and homework
It was very important to you to really understand the physics
Consistently seeking ways to improve
You did solitary, deliberate practice
You felt comfortable of your ability in the physics class
You could achieve high levels of concentration and focus
You lacked confidence in your ability
You managed your time well for study, revision, monitoring progress.

You were able to progress in physics in spite of adversity in your life

You took part in enrichment activities such as: Science Club, Physics/Engineering Events, Physics Olympiad, Nuffield Research Placement, Arkwright Scholar, CREST awards, Engineering Scheme, etc.

19. Your learning behaviour during physics lessons. Please select no more than 14 answer(s).

You listened intently during lessons

You usually asked and answered questions

You were a key contributor to questions and answers

You questioned and sought evidence to ensure you understood rather than learn off.

You took an active role in discussion and debate

You were keen for the teacher to go beyond the syllabus or to more depth.

Your involvement and learning behaviour in lessons was typical of most of the students.

You were quiet in class but actively working to get to your own level of understanding

At times you lost track in lessons and had to catch up outside lessons

You accepted that there were just some topics you would never understand.

You made a strong contribution to lab work or demonstrations

You helped other students with their work and understanding of physics.

You read beyond the syllabus /did extra questions

You always struggled with the subject and scraped through.

You were good enough and did OK in marked work

You were good and got good marks

You were very good and most often scored high marks

19.a. If you were part of a minority set within the class, did this have any impact on your learning, positive or negative? Describe the minority set and the impact

20. What was your ‘Physics Identity'. Select ALL that apply

You were the 'go to' person for anything physics related - sure to understand and explain.

Irrespective of your exam grade you were passionate about physics

You had the ability but did not apply yourself and underachieved

You underestimated your ability and could have done better

You were a gifted student with great potential

You were a solid, steady, hardworking student

You were able to do well without much effort

You were a 'natural' physicist

Doing physics was highly absorbing

Doing physics was intrinsically rewarding

You could be described as a Blue Sky thinker creating compelling and original ideas.

Others (teachers, peers, parents) also rated you in this way

You were indifferent to how others viewed you as a student

21. What influenced you to choose advanced level physics at school - select ALL that apply to you from the list below?

You always enjoyed physics - it fascinated you
You were good at physics -good grades
You felt a sense of belonging to the Physics group
A teacher /school member encouraged you to keep up physics
Subject choices were limited to groups - so you had to choose physics
It was important or necessary to choose all three sciences
You wanted a career in a physics/engineering related field
You needed physics for a future non-physics career - e.g. medicine
Physics opens the most career opportunities
Your Parents/Guardians/Siblings were in science related careers
To prove to yourself/others that you could succeed at physics
People regard you as clever with a physics qualification

21.a. Were there challenges that you had to overcome or pressures to resist to stay on course with your physics study.

21.b. Considering you childhood play, hobbies, your upbringing and experiences of your youth, are there any aspects that you would now consider improved your ability to do physics.

Research Ethics

This research was approved by the University of Leeds, School of Maths, Physical Sciences and Engineering Research Ethics Committee on 4th May 2018 ref MEEC 170024

Appendix C Question 12

Question 12 in the questionnaire stated.

With hindsight how would you now describe yourself as a physics/science student at secondary school: From the list below please choose ALL statements which best describe the type of student you were. The characteristics are purposely listed in a random order and you should choose without much deliberation.

In the Questionnaire as set out in Appendix B note that the 69 statements are not numbered. However to identify each statement for data analysis and presentation in figures and tables, each was assigned consecutive numbers as shown below.

Q12_1	you loved physics
Q12_2	physics was ok as a subject and you could do it
Q12_3	you really didn't like physics; knew it was an important subject need
Q12_4	you had to work hard to understand physics
Q12_5	you had an inherent talent for physics
Q12_6	others viewed you as a definite scientist/engineer
Q12_7	curious/inquisitive
Q12_8	liked a challenge
Q12_9	tenacious
Q12_10	you were inspired or enthused by a role model
Q12_11	conscientious
Q12_12	quick minded
Q12_13	good at abstract thought
Q12_14	liked science experiments
Q12_15	a good head for facts
Q12_16	quick recall of relevant knowledge
Q12_17	patient and persistent in your studies
Q12_18	saw yourself as a physics person
Q12_19	academic / geek / nerdy
Q12_20	recognised yourself as a future scientist, physicist or engineer
Q12_21	loved to study

Q12_22	aware of your learning - had learning and studying strategies
Q12_23	determined to see a task through to the end
Q12_24	a problem solver
Q12_25	methodical
Q12_26	inventive
Q12_27	able to spot your own errors
Q12_28	liked to be rated as clever
Q12_29	systematic: you liked to create order and produce diagrams, tables etc.
Q12_30	liked to see the big picture
Q12_31	could work independently
Q12_32	quietly confident in your abilities
Q12_33	enjoyed working with mathematics
Q12_34	able to present your ideas clearly and accurately
Q12_35	enjoyed building mental models - seeing with your mind's eye
Q12_36	liked the iterative nature of building understanding
Q12_37	resilient to set backs such as getting the answer wrong
Q12_38	believed in practice makes perfect
Q12_39	sometimes or often solved questions differently to others - innovative
Q12_40	enterprising - thinking differently and striving to improve
Q12_41	resourceful - you would find a way to do what it takes - can do attitude
Q12_42	you were an ideas' person, reflecting and playing with ideas
Q12_43	logical
Q12_44	not put off by complex or ambiguous concepts and questions
Q12_45	achievement motivated
Q12_46	you learnt from your mistakes
Q12_47	took great pride in your physics knowledge
Q12_48	loved working with equations and formulae
Q12_49	got a buzz out of physics
Q12_50	was important that through physics could make the world a better place

Q12_51	worked quickly through calculations
Q12_52	had a feel for numbers
Q12_53	liked how physics explained so much of everyday life
Q12_54	liked talking physics/mathematics/ engineering
Q12_55	you could do a number of stages of a problem in your head
Q12_56	knew when you were on the right tracks
Q12_57	liked the accurate use of language in physics: scientific terms/ formulae
Q12_58	could usually come up with new idea to solve a problem
Q12_59	enjoyed expanding ideas when getting to grips with a new topic
Q12_60	good at recognising links in information, experiments and data
Q12_61	good at recognising patterns in information/numbers/observations etc.
Q12_62	observant - you had an eye for detail
Q12_63	hard working - put in the effort
Q12_64	you found physics intuitive -understanding phenomena came with ease
Q12_65	you liked to help others with understanding physics
Q12_66	key knowledge came to mind unconsciously
Q12_67	often used your initiative in lab work and problem solving
Q12_68	you were good at Mathematics
Q12_69	you were good at English

Glossary

A Level Advanced Level, the standardized British examination, General Certificate of Education in a secondary school subject used as a qualification for university entrance

O Level the basic level of the General Certificate of Education now replaced by GCSE

OCED The Organisation for Economic Co-operation and Development is an intergovernmental economic organisation with 38 member countries, founded in 1961 to stimulate economic progress and world trade. This organisation collects and analyses data on academic performance among its member countries with the aim to improve education standards for all.

Emic This is one of a pair of qualitative evaluators *etic* and the *emic*. These are terms usually used by anthropologists. The etic perspective is the outsider's perspective. The emic perspective is the insider's perspective, the perspective that comes from within the culture where the project is situated—for example, gender. The emic helps understanding local realities, and the etic helps in the analysis of the reality.

Phenomenography is a qualitative research methodology, within the interpretivist paradigm, that investigates the qualitatively different ways in which people experience something or think about something. It is an approach to educational research which appeared in publications in the early 1980s.

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